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[*Continued on page (III) of Cover.*

THE EMPIRE SERVICE BROADCASTING STATION AT DAVENTRY

By L. W. HAYES, Member, and B. N. MacLARTY, O.B.E., Associate Member.*

(*Paper first received* 16*th September*, 1938, *and in final form* 1*st June*, 1939; *read before* THE INSTITUTION 2*nd February*, *before the* NORTH-WESTERN CENTRE 31*st January*, *and before the* SCOTTISH CENTRE 28*th March*, 1939.)

SUMMARY

The paper describes the development of the short-wave broadcasting service in this country during 11 years from the initial experiments carried out at Chelmsford in 1927 to the present time. As a result of the initial experiments, the Empire broadcasting station was established at Daventry by the B.B.C. in 1932. The considerations underlying the design of this station are given, together with a brief description of it and the results obtained. Changes to the 1932 aerial system are discussed and an account is given of a series of experiments carried out at Daventry to determine the most suitable type of aerial for short-wave broadcasting. Details are given of the new aerial system erected at Daventry as a result of these experiments.

The number and power of transmitters required for a short-wave broadcasting service which has to cover practically the whole world are discussed, and a detailed description is given of two types of high-power short-wave transmitter which have been installed at Daventry. The feeder and feeder-switching system to permit the connection of a number of high-power transmitters to a number of short-wave aerials is described. The paper ends with information on the performance of the station. An Appendix contains notes on the wavebands available for short-wave broadcasting services.

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CONTENTS—*continued.*

(1) BEGINNING OF THE SERVICE

(a) Initial Experiments

In November, 1927, the B.B.C. inaugurated a series of experimental transmissions of items from their programmes on a short wavelength of 24 m. (12·5 Mc./sec.) from a transmitter at the Chelmsford works of Marconi's Wireless Telegraph Co., Ltd. This transmitter was of the standard beam type and delivered a power of from 8 to 10 kW to a Franklin uniform aerial suspended from a triatic carried by two 475-ft. tubular steel masts.

During 1928 the wave was changed to 25·53 m. (11·75 Mc./sec.) in order to conform to the international allocation of wavelengths contained in the Washington Radiotelegraph Regulations.

At the time the experiment was begun it was known that a keen interest in short-wave reception existed among amateur experimenters abroad. The object of the experiment was to ascertain whether a more general interest existed, or was likely to be created if at a later date a more comprehensive short-wave service were inaugurated.

The experiment was necessarily prolonged, but it provided the information sought. A genuine listener interest did exist which was prepared, if necessary, to put up with the vagaries of short-wave reception if it was at the same time given the opportunity of hearing

* British Broadcasting Corporation.

news bulletins and partaking in national events broadcast from London. This interest was naturally greater in the Colonies and in those parts of the Dominions where there were no local broadcasting services.

On the technical side the experiment showed that a short-wave transmitter situated in England and working on a single wavelength, could provide intelligible reception at some time of the year to almost every British Dominion and Colony, although reception was much better in some parts of the world than in others. It appeared that the use of two transmitters simultaneously working on different wavelengths would materially increase the periods of good reception. It also appeared that it would be desirable for the transmitters to be capable of adjustment to wavelengths in each of the wavebands between 13 and 50 m. allotted to broadcasting under international agreement (see Appendix). The use of directional aerials in place of the non-directional aerial at G5SW Chelmsford offered possibilities of increased signal strength at the point of reception if the practical difficulties associated with their use in broadcasting to an Empire which subtends an angle of some 320° at Daventry could be overcome.

The question of the provision of suitable receivers was not overlooked. It was realized that, with the receivers then existing, considerably more skill was required of the short-wave listener in tuning-in a distant short-wave station than could be expected from the average listener. For this reason many would not get the results which could be expected from a similar instrument in the hands of a skilled operator. Nevertheless, there appeared to be little doubt that if a service were established on a more comprehensive basis, great advances in the design of suitable receivers for individual listeners would follow automatically.

(b) The original Empire Broadcasting Station at Daventry, 1932

This paper would be incomplete without a reference to the original short-wave station erected at Daventry in 1932 and opened on the 19th December of that year, although the original aerial and feeder system has already been replaced and the two transmitters are no longer in regular service. Before describing the aerial system, it is first necessary to examine some of the problems which underlie the provision of a broadcasting service to the Empire.

The first factor is the wide difference in longitude of the various Dominions and Colonies. A reference to Fig. 1 will show this. It is evident that it is necessary to provide a service in the various parts of the Empire at a convenient listening hour for local reception. In broad terms it may be said that this falls somewhere between the hours of 6 p.m. and midnight, local time, since there must inevitably be variations of time within a zone itself. This difference in longitude is at once an advantage and a disadvantage when looked at from the transmitting end: an advantage, because transmissions can be carried out "in series" and a smaller number of transmitters used; and a disadvantage, because it becomes necessary to transmit at times outside the normal programme hours in this country, with attendant increase in programme expenditure and/or recourse to recording.

The second factor is also concerned with the geographical disposition of the Empire countries with regard

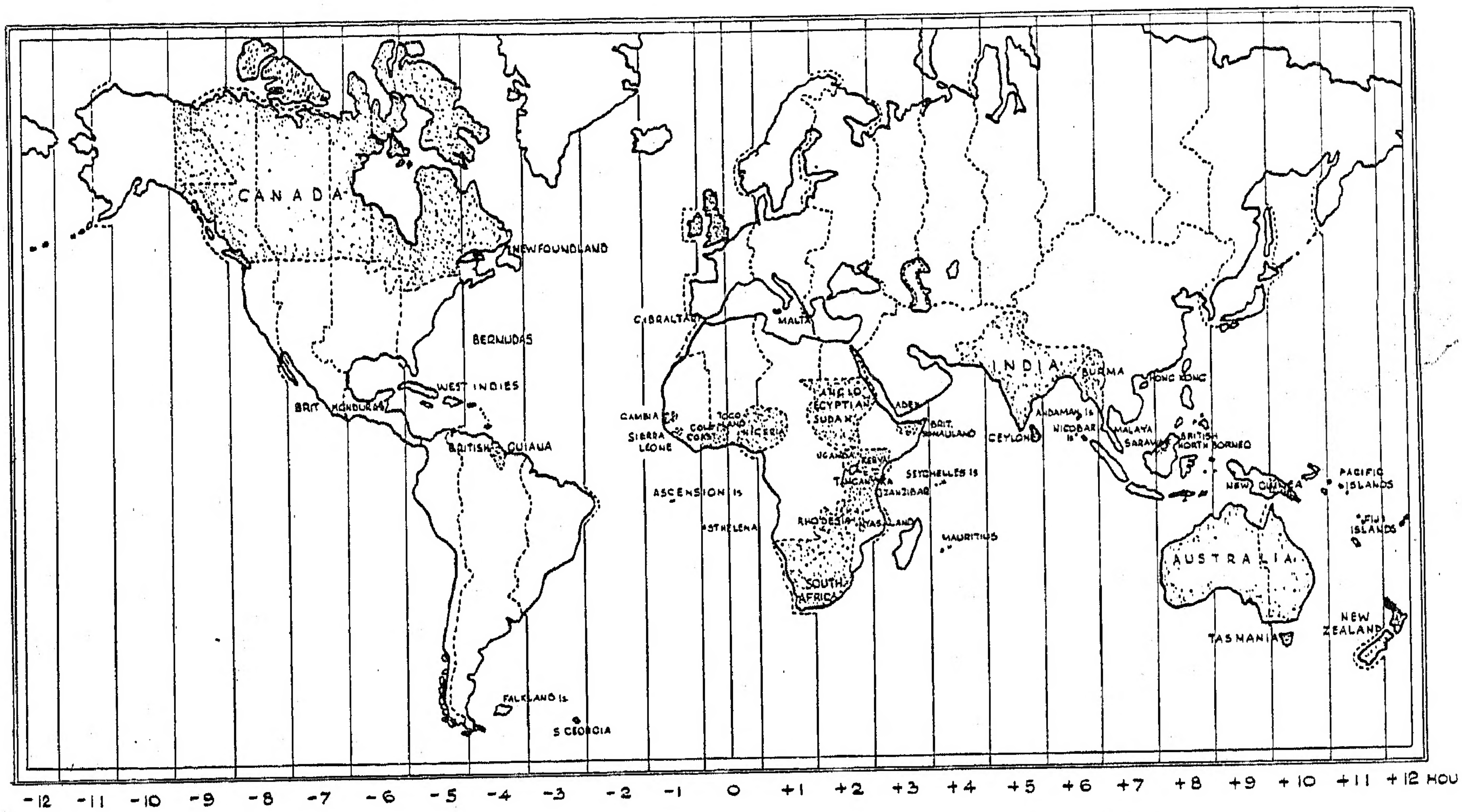

Fig. 1.—Time-zone map of the world, showing the countries of the British Empire.

to Daventry, and determines the possibilities of the use of aerials which are directional in the horizontal plane as opposed to aerials which are non-directional in this plane. A reference to the projection of the world given in Fig. 2, which shows the layout of the world with regard to London, indicates at once that advantage can be taken of directional transmission.

Zone 4 .. West Africa (including Nigeria and the Gold Coast) and the Atlantic islands.
Zone 5 .. Canada, West Indies, Trinidad, British Guiana, and the Pacific islands.

For some of the zones 3 separate aerials were provided to give transmission on 3 separate wavelengths, which

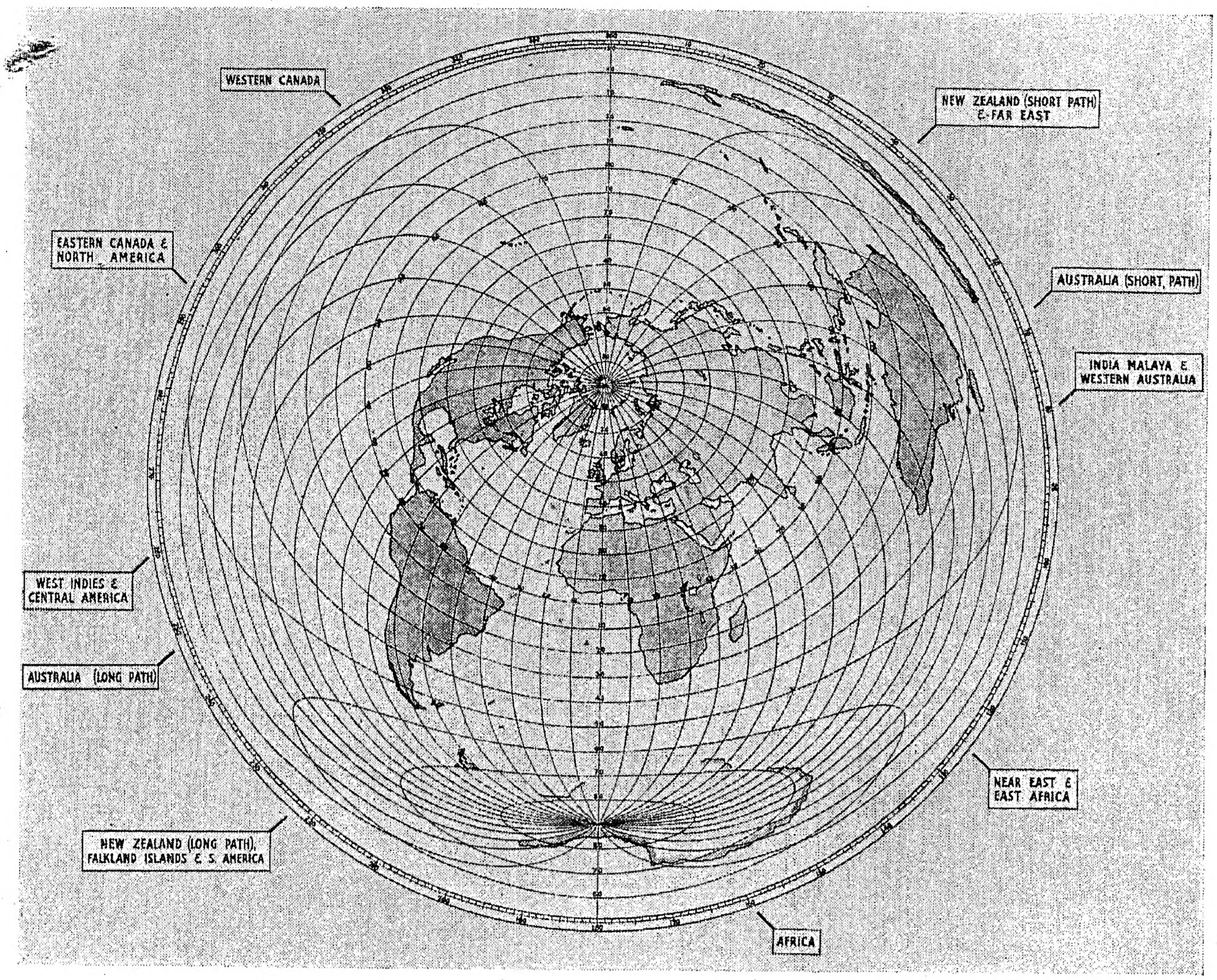

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Fig. 2.—Map of the world on Plett's zenithal azimuthal projection, showing the true direction of every point in the world from London. If a straight-edge be laid along the line joining London and the required place, it will indicate on the peripheral protractor the true bearing in degrees measured from the North. The approximate directions in which the various Empire transmissions are radiated are as shown.

The third factor concerned the suitability of the different short-wave bands for transmission over the required routes at the time of day during which it was desired to transmit.

After careful consideration it was decided to divide the Empire into 5 zones, each zone being provided with a directional aerial system, as follows:—

Zone 1 .. Australia, New Zealand, and Borneo.
Zone 2 .. India, Burma, Federated Malay States, and Straits Settlements.
Zone 3 .. South Africa, East Africa, Sudan, and Somaliland.

it was thought would be necessary to take account of changing conditions of day and night, winter and summer. The layout of the aerial system is shown in plan in Fig. 3. Six non-directional aerials (one for each wave-band) were provided in addition to the directional aerials to take account of any special transmissions which might be necessary outside the normal schedule of directional transmissions.

Each directional aerial consisted of a radiating curtain of vertical elements behind which was placed a reflecting curtain of similar elements, each element consisting of a vertical dipole slightly less than $\frac{1}{2}\lambda$ long, fed at the centre by a 2-wire feeder. This feeder was tapped

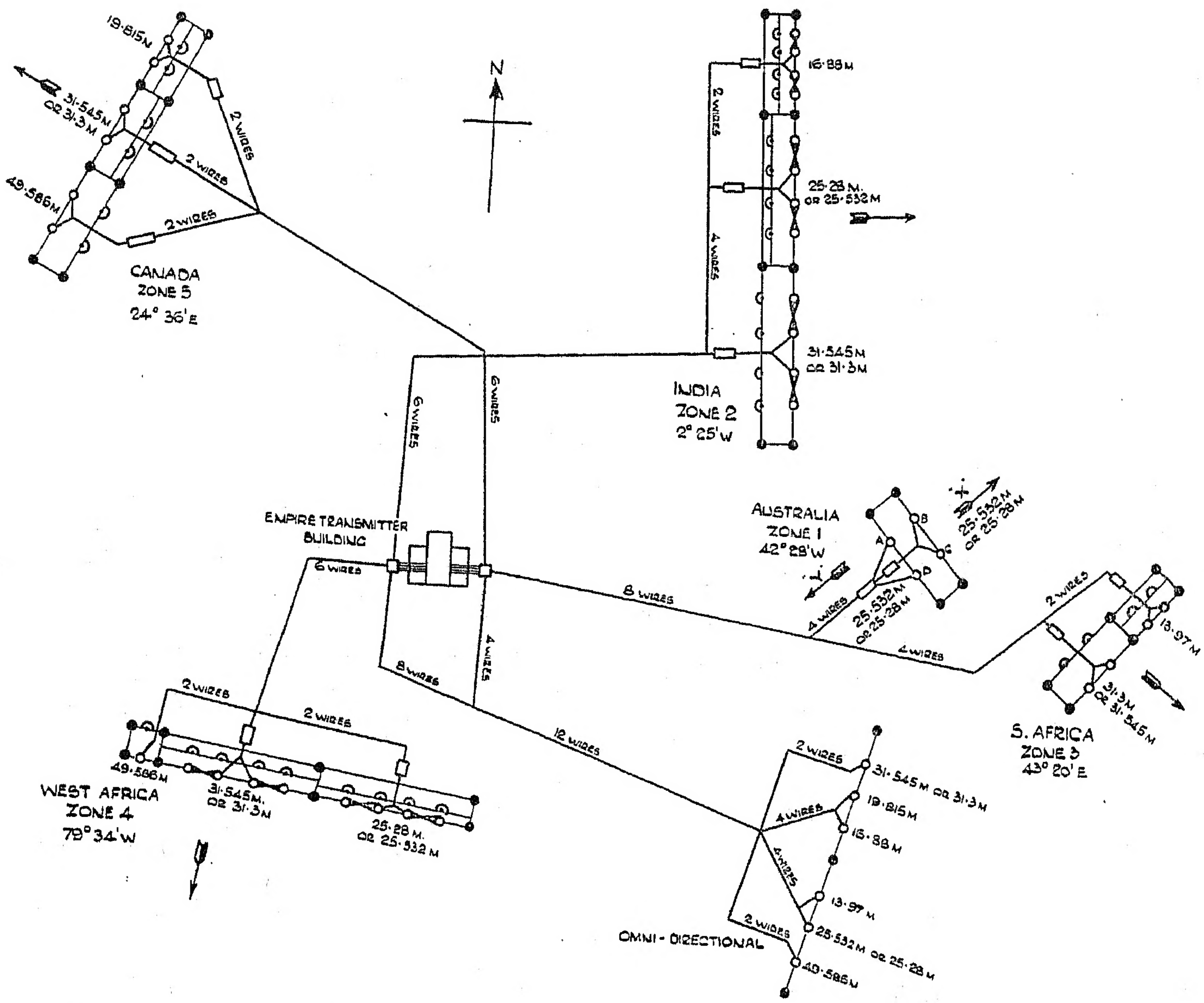


Fig. 3.—Layout of 1932 aerial system at Daventry.

across a coil connected at the centre of the dipole. The reflector curtain was suspended a $\frac{1}{4}\lambda$ behind the radiator curtain. Reference to Fig. 3 will show that one of the aerials contained only one radiating element, while others contained two elements, and those for the Indian zone four elements. The 4-element aerial had a narrower beam and greater concentration of energy in the required direction, as this zone subtended a relatively smaller angle at Daventry than the other zones. Fig. 4 shows the arrangement of a 4-element aerial.

The whole aerial system was supported on steel tubular masts 80 ft. in height. The use of relatively low aerials may be thought to be open to criticism in the light of the results of later experiments made at Daventry and described in a subsequent Section of the paper. It must be remembered, however, that a broadcasting service has to cover great areas at varying distances from the transmitter, and there was no evidence to show whether the aerials found suitable for a point-to-point service would be suitable for a broadcasting service. High aerials imply the use of high masts, which are much more costly than low masts and, once erected, cannot be moved except at considerable expense. In order to ensure maximum flexibility and lowest first cost, the initial use of low aerials at Daventry was justified.

The 1932 station contained two low-power-modulated transmitters each capable of supplying a power output of 10 to 15 kW to the feeders—the highest power being given on the longest wavelengths, viz. those in the 49-m. band. Arrangements were made so that either transmitter could work on any of the wavelengths assigned

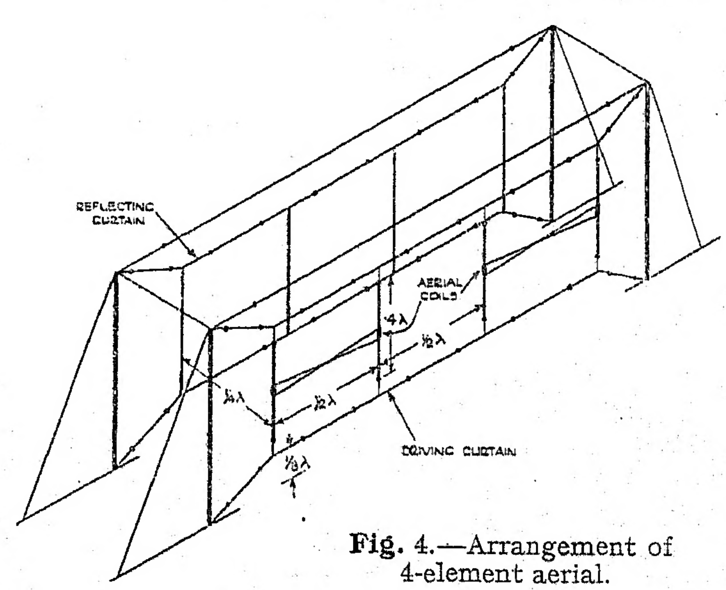


Fig. 4.—Arrangement of 4-element aerial.

to the station and be connected to any aerial. An open-wire feeder system was provided.

This installation, by means of which the Empire Broadcasting Service was opened on the 19th December, 1932, represented a considerable step forward from the

single-wavelength transmitter of 1927. From non-directional transmission of odd excerpts of the home programmes on one wavelength at times of the day which were not chosen for their suitability for the listening audience overseas, the service had grown to directional transmission on two wavelengths simultaneously—the wavelengths being chosen to suit the route in question—of programmes specially arranged for Empire reception and transmitted at times most suitable for local listening conditions in that part of the Empire to which transmission was directed.

(2) OPERATION OF THE SERVICE

(a) Aims of the Service

The initial programme schedule from the Daventry station was:—

Zone 1. The Australasian Zone
9.30 a.m. to 11.30 a.m. G.M.T.

Zone 2. The Indian Zone
2.30 p.m. to 4.30 p.m. G.M.T.

Zone 3. The African Zone
6.00 p.m. to 8.00 p.m. G.M.T.

Zone 4. The West African Zone
8.30 p.m. to 10.30 p.m. G.M.T.

Zone 5. The Canadian Zone
1.00 a.m. to 3.00 a.m. G.M.T.

The choice of hours was based primarily on consideration of the listeners' convenience, but it was realized that these timings were experimental and might need modification in the light of reports.

Broadly, the aim of the service was to give listeners anywhere in the Empire a daily programme of about 2 hours' duration, and, as will be seen from the above schedule, the station initially worked for 10 hours a day in five 2-hour periods. In a short-wave service, where propagation is not by direct but by indirect radiation, it is not possible to assure satisfactory results for 100 % of the time. At its best, the service approaches very closely to that given in the primary area served by a medium-wave broadcasting station by direct radiation. At its worst, nothing at all is received by the listener. The concern of the transmitting engineer is therefore to ensure that the service shall approach as nearly as possible to its best *for as large a percentage of the transmitting time as possible,* although 100 % service is an ideal not likely to be reached in any short-wave service. The receiving end plays a large part in the overall result, but in a broadcasting service of any kind reception must be judged principally on the assumption of commercial broadcast receivers in the hands of individual listeners, and connected to aerials which these listeners can erect at their own homes.

(b) Results Obtained with the 1932 Station

In spite of the good response from listeners and the initial success of the station, it was felt that the proportion of time when reception was really good was not sufficiently high. In particular it was evident from the correspondence that, while reception reached a reasonable standard frequently throughout the year in certain parts of the Empire, and frequently during certain seasons in other parts of the Empire, the overall percentage of good reception time required improvement if the original aims of the service were to be achieved.

A number of changes in timing of programmes and additions to the original schedule were made in 1933.

A further stage in the development of the service was marked early in October, 1933, by the introduction of alterations in the designation of zones and the timing of transmissions. The daily transmissions from the Empire Station were divided into five sessions known as Transmission 1, Transmission 2, etc., in accordance with the time schedule given below. A sixth transmission was added in 1935, primarily intended for evening listening in Western Canada, but serving also North America generally and giving an early-morning service to India.

Transmission	Time, G.M.T.
1	Two-hour period, the starting time changing from month to month between the limits of 4.30 a.m. and 8.00 a.m. to ensure a satisfactory service in Australasia.
2	12 noon to 1.45 p.m. weekdays; 12.30 p.m. to 1.45 p.m. Sundays.
3	2.00 p.m. to 6.00 p.m.
4	6.15 p.m. to 10.45 p.m.
5	11.00 p.m. to 1.00 a.m.
6	2.00 a.m. to 4.00 a.m.

This transmission schedule has, with minor alterations and extensions, remained in force.

(c) Contact with Listeners

The broadcast engineer is not in the happy position of the engineer responsible for a point-to-point service. The former operates a one-way service, the latter a two-way, and the latter is therefore in the position of being able to obtain instant information on the reception of his signals. If changing propagation conditions demand it, he is immediately informed that a change of wavelength is necessary. The broadcast engineer, on the other hand, must make his choice in advance and adhere to it until he can announce to his listeners that a change is to be made. For this reason it has been found desirable to broadcast to a given area on two waves simultaneously, the waves being chosen to cover probable changes in propagation conditions during all or part of a transmission, although a limitation in the number of transmitters available makes it impossible to follow this throughout the service.

The task of collecting technical information from listeners in the most suitable form was carried out by sending pads of log sheets to about 50 selected listeners covering the whole Empire. In order to secure uniformity of judgment, a gramophone record was made giving the B.B.C.'s idea of what was meant by Merit 1, Merit 2, etc., reception, and a copy of this record was sent to each log-sheet keeper. In this way it has been possible to provide in Broadcasting House an almost complete record of reception conditions on all transmissions in the various parts of the Empire to which they were directed. This has recently been supplemented by a cable reporting scheme by which some 25 observers (official and private) send each week-end a letter telegram to Broadcasting House

reporting, in 25 words, on the reception of the transmissions directed to them in the previous week.

(3) DEVELOPMENT OF THE SERVICE

(a) Changes in Aerial System to Secure Better Coverage

In spite of the improvement in percentage time of good reception achieved by the transmission-schedule changes already described, there appeared to be no doubt as to the desirability of giving a generally stronger signal to listeners, and the questions of aerial design and the number and power of transmitters came under consideration. The series of aerial experiments had as their principal object the provision of aerials which would give the listener the best signal for a given transmitter power and a given horizontal polar diagram.

The horizontal diagram required is a matter of fairly easy determination. On the one hand, there is the non-directional aerial with which one transmitter can provide a relatively weak signal to a large area, while on the other hand there is the highly directional beam aerial used in a point-to-point service, by means of which the same transmitter can provide a strong signal at a given receiving station and to a relatively restricted area round it. A compromise must be found between a large number of narrow beams (implying a large number of transmitters and aerials) each covering a small area with a strong signal, and a small number of broadcasting—in the literal sense—aerials each covering a large area with a weaker signal. From the operational point of view a smaller number of non-directional aerials has much to recommend it, but the effective power gain to be obtained from directional transmission is considerable and cannot be forgone if the listener is to be given a really first-rate signal. The compromises decided on for the Empire station were such that for most of the aerials the signal in directions 18° off the centre-line of the main directions of transmission is 6 db. below that given on the centre-line, and the effective area considered to be covered is thus a sector subtending 36° at Daventry. For certain special requirements two broader-beam aerials were provided from which the signal in directions 34° off the centre line is 6 db. below that given on the centre-line, and these aerials cover sectors subtending 68° at Daventry. Places outside these sectors also receive some service, but for design purposes these figures have been adopted. Directional transmission of this kind cannot properly be termed "broadcasting," nor is it "beam" transmission in the commercial point-to-point service sense, where radiation is effectively concentrated within an angle of 3° to 10° on either side of the centre-line. The term "narrow-casting" has been suggested, and seems not unsuitable for the intermediate class of transmission here described, which is intended for reception by the general public within a more or less restricted area.

The decision to use aerials covering a smaller sector than those originally erected at Daventry involved the provision of a larger number of aerials. Experience in the day-to-day running of the service had shown that a greater choice of wavelengths for certain directions would be desirable to secure optimum propagation conditions and to take account of service outside the normal hours. It was accordingly decided to provide aerials to give transmission as shown in Table 1.

In general, the centre-line of transmission was chosen to coincide with the actual bearing of the place or mean bearing of the places where a relay receiving station was likely to be situated, e.g. mean bearing of Sydney and Melbourne, mean bearing of Johannesburg and Cape Town, bearing of Buenos Aires and Rio de Janeiro, bearing of Montreal, etc. This can be seen by comparing the directivity of the aerials with the bearings of the principal centres shown in Fig. 5.

Table 1

Area served	Bearings, degrees E. of true N.	Wavelengths, in metres
1. New Zealand (short path), The Far East	44	19, 25, and 31
2. Australia (short path) .. Australia (long path) ..	68 248	19, 25, and 31
3. India, Malaya, Ceylon ..	80	14, 17, 19, 25, 31, and 49
4. East Africa, Eastern Mediterranean	126 135	31 and 49 19
5. South Africa	160	25 and 31
6. Africa generally ..	160	14 and 17
7. West Africa	175	19
8. New Zealand (long path), The Falkland Islands, and South America	224	14, 17, 19, 25, and 31
9. West Indies	260	14, 17, 19, 25, 31, and 49
10. Eastern Canada, United States of America	294 306	14, 17, 19, 25, 31, and 49
11. Western Canada	315 324	19 25 and 31

In the practical layout, transmission on 44° is given by reversing the direction of transmission of the 224° aerials and transmission on 68° and 248° by electrically "slewing" the direction of radiation from the aerials, which also give transmission on 80° and 260° by reversal of the reflectors where provided. Transmission on 135° is given by reversal of the 315° aerial, and transmission on 324° is given by reversing and slewing the direction of radiation from the 160° aerials. The 126°/306° bearing was determined by the position of the existing 500-ft. masts originally used for the Daventry 5XX long-wave transmitter.

At the present time, aerials are being added to give

duplicate transmission on 224° in the 17-, 19-, 31-m. bands and on 260° in the 19- and 31-m. bands to take account of simultaneous transmission of programmes in English, Spanish, and Portuguese to South and Central America. No extra aerials are being provided for the Arabic transmission which has also been instituted, as the zone concerned can be covered on the Canadian 294° aerials reversed to give transmission on 114°—Canada not requiring service during the Arabic transmission timings.

The question of the vertical polar diagram of aerials is a much more elusive one, yet one of great importance if the optimum propagation conditions are to be achieved. Walmsley dealt with this question in detail in a paper read before the Wireless Section* and showed, *inter alia*,

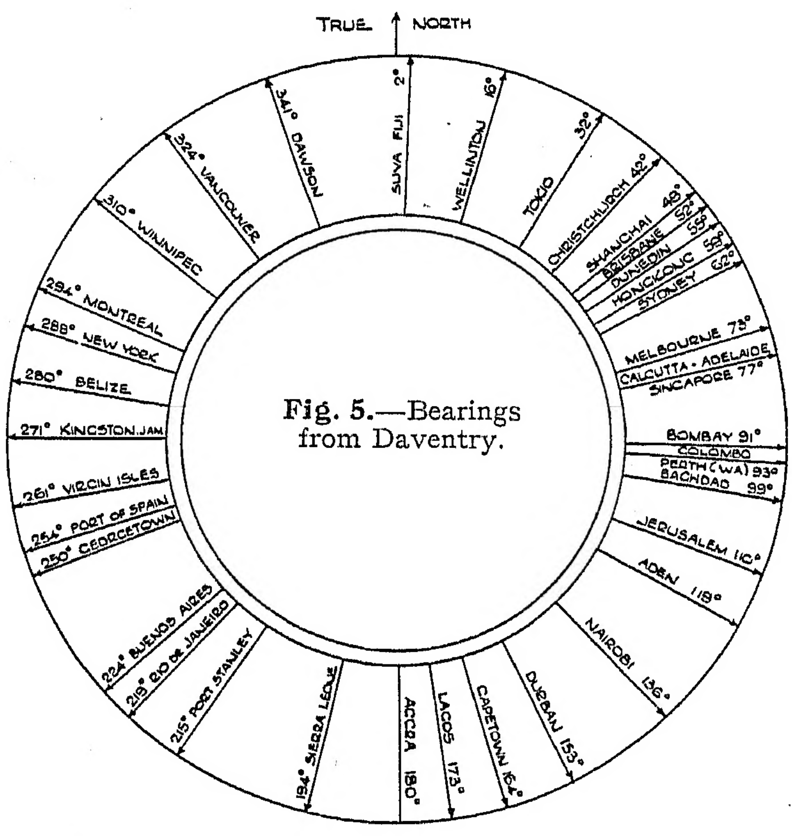


Fig. 5.—Bearings from Daventry.

that it was impossible to predict the optimum diagram in advance and that it was necessary to adjust the angle of the main lobe of radiation and its width in the vertical plane to suit the particular propagation path. The determination of the optimum vertical polar diagrams of aerials at Daventry was therefore left to the results of a series of practical experiments which are described in a later Section of the paper.

(b) Number of Transmitters

The two transmitters of the 1932 station soon proved insufficient in number to carry the service, particularly on occasions such as H.M. King George V's Christmas Day broadcasts and the Silver Jubilee programmes, when it was required to serve practically the whole Empire at one and the same time. The aerial experiments, too, made it desirable to have another transmitter available, and accordingly the old G5SW transmitter from Chelmsford was installed at Daventry in the spring of 1935. This transmitter has since been increased in power to give an output of 20 kW and modified so that it can work on a number of wavelengths. It is now used in all transmissions.

With the decision to provide a new aerial system consisting of aerials which covered narrower areas than the original aerials (but of course with stronger signals) the question of the number of transmitters required further consideration. In the limit, if it were required to cover the whole Empire simultaneously with one programme it would be necessary to have 9 transmitters each covering 36°, for Empire countries subtend approximately 320° at Daventry and unidirectional transmission is considered desirable.

For the day-to-day transmissions, however, a smaller number will give adequate coverage. For instance, in Transmission 1, Australia and New Zealand subtend between 80° and 90° at Daventry, so that four transmitters would allow most of the area to be covered twice, i.e. on two wavelengths for each of two directions. Four transmitters would also be adequate in Transmissions 2 and 3 and in the earlier part of Transmission 4 to cover the primary areas. In the later part of Transmission 4, and in Transmission 5 when service has to be given to the American Continent, it is necessary to transmit in three different directions simultaneously—to the south-west for the Falkland Islands and the large British population in Argentina (particularly Buenos Aires), to the west for the West Indies, and to the north-west for eastern Canada and Newfoundland. While the total angle subtended at Daventry is not much greater than that subtended by Australia and New Zealand, an attempt to cover the area with two directional transmissions would result in the strongest signals being given in areas in which they are not required, and in the provision of weaker signals to the areas it is desired to serve. Six transmitters would therefore be required to give two-wavelength transmissions of one programme to those parts of the American Continent where the time-difference from Greenwich is between 4 and 6 hours slow. Western Canada, with 7 and 8 hours' time-difference, can be served later on and need not be considered in Transmissions 4 and 5.

It was ultimately decided that Daventry should have 6 transmitters, i.e. the three transmitters already mentioned and three new ones of higher power, but that the building to house the three new transmitters should be made large enough to house four. Work on the new station and aerial system was started in 1936. The remainder of 1937 and the first months of 1938 saw the completion of the new station, but by this time further extensions had been planned consequent upon the decision to broadcast in foreign languages from Daventry.

In order to carry this extra service, involving at the outset the transmission of news in Arabic, Spanish, and Portuguese, without detriment to the Empire service, it was decided to provide a further two higher-power transmitters and to house them in an extension to the new building large enough to house 4 such transmitters. There will therefore be sufficient room for a total of 8 higher-power transmitters.

(c) Power of Transmitters

The gain in signal obtained by power increase at the transmitter has been aptly termed "gold-plated" decibels by an American contemporary, and it is a gain which does

* *Journal I.E.E.*, 1934, vol. 74, p. 543.

not depend on propagation conditions as does the gain obtained by change in aerial design. In a service which works for many hours a day, it is an expensive method of obtaining gain, and from this point of view it should be the last resort, but in a short-wave broadcast service it is impossible to count on gain of receiving aerials or on too great an increase in gain by limiting the width of the transmitted beam. Other methods of obtaining an improved signal-to-noise ratio, such as the use of single-side-band transmission with suppressed or partially suppressed carrier, are also denied to the broadcast engineer—at least in the present state of the art. He is therefore forced to use the highest possible power. Even then he cannot hope to provide as good a signal-to-noise ratio in disturbed conditions as is desirable for good broadcast transmission, which demands a signal-to-noise ratio of about 40 db. Considering only the gain of a specially designed receiving aerial, 15 db. can be fairly easily obtained in comparison with an average listener's aerial. This represents a power ratio of 32 to 1, or 320 kW at the transmitter in place of 10 kW.

In 1935 the highest-power short-wave broadcast transmitter commercially available was capable of delivering a power of 40–50 kW to the feeder on the medium and longer short waves. This power was not considered sufficient for the future, and it was felt that in constructing a new station at Daventry a higher power was desirable. It was ultimately decided in consultation with the manufacturers that a power of about 100 kW would be possible on a commercial basis, and transmitters of this size were accordingly ordered by the B.B.C. The high-frequency switching and feeder system and the aerial system were also designed to be capable of dealing with this power on wavelengths from 80 m. down to 13·9 m.

It should be mentioned that the higher-power transmitters at present installed at Daventry are not being worked at full power but at the power for which the station is licensed by the Postmaster-General, namely 50 kW delivered to the aerials.

(4) AERIAL AND MAST DESIGN

(c) Experiments on Performance of Aerials

The purpose of this Section is to record the series of aerial experiments which were carried out at Daventry to ascertain the type of aerial most suitable for use there, with particular reference to signal strength at the receiving end, and to give the theoretical power distribution through space of the types of aerial selected as a result of the experiments.

Early in 1933 it became evident from reports received that the Daventry signals were weaker than might have been expected. It appeared that the deficiency was largely due to the relatively poor performance of the transmitting aerials. It was therefore decided to use the masts which supported the aerial of the long-wave station 5XX at Daventry to support some simple horizontal dipoles, and to compare their performance with that of the low vertical aerials. The first experiment was carried out in May, 1933, and compared directly a high horizontal $\frac{1}{2}\lambda$ dipole with one of the low vertical non-directional aerials. The results were surprisingly definite and the high aerial showed a gain of 5 to 10 db. in Buenos Aires and in Bermuda. From other parts, which were not on or near the minima of the horizontal dipole, qualitative reports of the improved signals were received. In December, 1933, a high horizontal $\frac{1}{2}\lambda$ dipole for 31 m. was compared with the 31-m. 4-element low vertical Indian aerial and was found to give equal-strength signals on the centre line of the aerial (Ceylon). The theoretical gain in signal of the 4-element array in the horizontal plane was 9 db.

At this time it was not obvious whether the improved performance of the experimental aerials was due to their being horizontal as opposed to vertical, or to their being high as opposed to low, and a further experiment was therefore carried out—on 19 m.—in which a vertical dipole was supported on the 5XX masts. A fair amount of evidence was received which showed that the elevated vertical aerial gave no improvement over the low vertical aerial. It was realized that this poorer performance of the high vertical dipole, in comparison with that of the high horizontal dipole, might be due to difficulties in feeding this type of vertical aerial.

It was next decided to carry out experiments with simple forms of aerial arrays, viz. stacked horizontal dipoles, compared with vertical aerials of the Franklin uniform type. It was desired to choose between horizontal and vertical aerials and, at the same time, to ascertain the minimum mast height required for satisfactory performance. Two 350-ft. towers were accordingly built to allow a number of arrays to be erected.

The aerials tested, all on 25 m., were as follows:—

(1) A Franklin vertical uniform aerial.
(2) A modification of (1).
(3) A modification of (1) (change of length of units).
(4) A modification of (3) (further changes to dimensions).
(5) A high $\frac{1}{2}\lambda$ horizontal dipole erected on one of the 5XX masts.
(6) A $\frac{1}{2}\lambda$ aperture horizontal aerial having 6 elements stacked one above the other at $\frac{1}{2}\lambda$ spacing with the bottom element $\frac{1}{2}\lambda$ above the ground.
(7) Horizontal aerial as (6) but with the bottom element 1λ above the ground.
(8) A $\frac{1}{2}\lambda$ aperture horizontal aerial having 4 elements stacked one above the other at $\frac{1}{2}\lambda$ spacing with the bottom element 2λ above the ground.
(9) As (7) but with vertical spacing between dipoles modified and the bottom element 1λ above the ground.
(10) As (8) but with the bottom element $0{\cdot}3\lambda$ above the ground.
(11) As (8) but with modified vertical spacing between the dipoles.

Fig. 6 shows these aerials diagrammatically.

Two aerials were erected at a time and used for comparative tests. Aerial (1) was tested in turn against (5), (6), (7), (8), and (9). These aerials were all designed to have the same horizontal polar diagram and, with the exception of aerial (5), gave optimum transmission on the same bearings, viz. 80° and 260°. The wavelength. bearings, and horizontal polar diagram employed in the experiments were chosen as they embraced a large number of listeners and it was possible to get reports of reception from New Zealand, Australia, Malaya, India, Ceylon, the

Near East, the West Indies, and from both North and South America.

Tests were carried out between November, 1934, and January, 1935, and the general result was that horizontal aerials (8) and (9) were both superior to vertical aerial (1). Although it was not possible to compare aerials (8) and (9) directly one against the other, comparison of each of them against aerial (1) indicated that aerial (8) gave slightly better results at distances beyond about 4 500 miles, while aerial (9) gave slightly better results up to that distance.

Attempts were then made to improve the performance of the vertical aerial (1); and between January and March, 1935, aerial (9) was compared successively with aerials (2), (3), and (4). In India, aerial (9) was reported as being 6 db. stronger in signal than aerial (3), and 4 db. stronger than aerial (4). Qualitative reports from listeners generally bore out these measurements. It was also reported that aerial (9) was superior as regards fading. It was concluded from these tests that horizontal aerials were more suitable for use at Daventry than vertical ones.

obtained in March and December may be explained by the change in ionization levels following the change in season, and the conclusion is then reached that, for optimum results, it would be desirable to use different vertical angles of transmission for day- and night-path transmissions and indeed for different seasons and periods of the sunspot cycle, a conclusion which was also found by Walmsley.*

So far only resonant-type aerials have been mentioned. The practical advantages of non-resonant-type aerials—such as the Bruce horizontal rhombic aerial—which make it possible to cover the broadcasting short wavebands with only one or, at the most, two aerials per direction, instead of one aerial per wavelength per direction, were not overlooked. The problem of feeder-matching at a high-power transmitting station is different from that at a receiving station, and although this type of aerial was known to possess simplicity and other advantages for the latter purpose, it appeared that most of the simplicity would be lost since it would be necessary to match the aerial to the feeder at each of the working wavelengths if maximum efficiency was to be obtained. Furthermore,

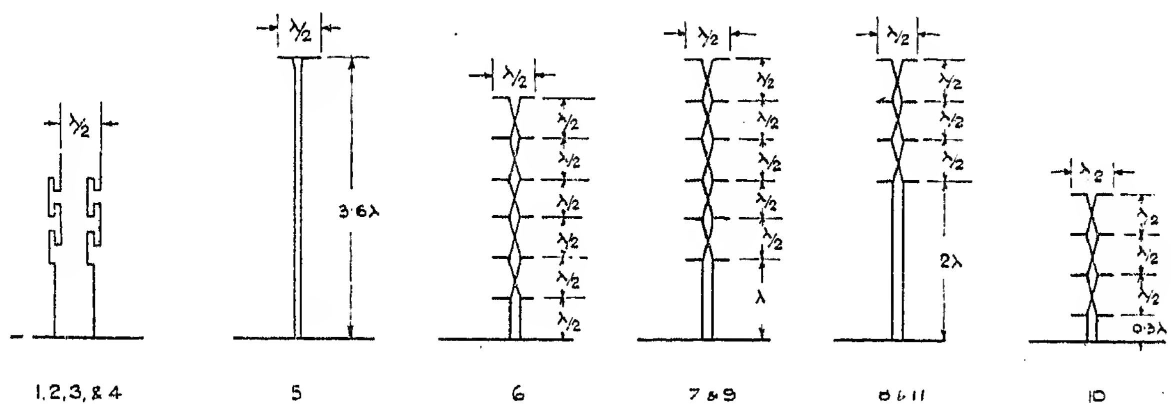


Fig. 6.—Types of aerials tested at Daventry.

In a subsidiary experiment carried out in October, 1934, a stack of 5 horizontal dipoles with the bottom dipole 1 λ above the ground was compared against a Franklin series phase aerial—both giving optimum transmission on a bearing of 160°. Reports from Africa were unanimous that the high aerial gave better signals, and measurements in Cape Town gave the difference in signal as 6 db.

In March, 1935, it was decided to make further comparisons between aerial (9) and a lower horizontal aerial —aerial (10). These tests gave the somewhat surprising result that aerial (10)—the lower one—gave stronger signals, particularly in India, than aerial (9), which appeared to be in direct contradiction to the results of the previous tests between aerials (6) and (7). Experiments with aerial (10) were continued. It was compared with aerial (8) and subsequently with aerial (11). From this series of tests it appeared that when transmitting from Daventry (in daylight) to the East (in darkness) aerial (10) gave slightly stronger signals. In general, it appeared that the lower aerial (10) gave better strength and less fading for day-path transmission, while the two higher aerials (8) and (11) gave better strength and less fading for night-path transmission. Generally speaking, all-daylight-path transmission was confined to India.

It is thought that the difference between the results

unidirectional transmission was generally desired in order to eliminate backward echo. With this type of aerial it is necessary to absorb power in a terminating resistance to secure unidirectional transmission, a method which is wasteful. For these reasons non-resonant aerials were not used at Daventry.

The conclusions drawn from the series of tests were:—

(*a*) Horizontal aerials are better than vertical aerials at Daventry.

(*b*) It is probably unnecessary to consider the use of aerials of more than 4 elements, one above the other, in the vertical plane.

(*c*) The bottom element should generally not be less than 1 λ above the ground, although in certain cases it may be desirable to increase this distance to 2 λ or to decrease it to 0·3 λ.

In January, 1935, the space between the 5XX masts became available for supporting aerials for the Empire service, and advantage was taken of their height to provide horizontal-dipole stacked aerials for 49, 31, and 25 m. for transmission on bearings 306° E. of N. (Canada) and 126° E. of N. (East Africa). A number of experiments were carried out to ascertain the optimum height, and the results confirmed the above conclusions.

* *Loc. cit.*

The new aerial system at Daventry was therefore designed on the above basis. This involved the provision of some masts 325 ft. in height to accommodate such aerials for 31 m. Fortunately, the 5XX masts were in the correct position to support the most important 49-m. aerial—that for Canada—and were 500 ft. high, thus allowing the erection of this same form of aerial. Since the service could not count on special types of receiving aerial having high gain, and as the gain from horizontal directivity could not be pushed to the limit possible in a point-to-point service, it seemed most desirable to achieve the full useful gain which could be obtained by optimum directivity in the vertical plane. It was considered desirable to secure good performance on 31 m., as waves on this band are in use for all transmissions, except Transmissions 2 and 3, throughout the year.

(b) Calculated Performance of Aerials

A large number of ordinary horizontal and vertical polar diagrams are necessary to evaluate the complete performance of a short-wave aerial. A knowledge of the power distribution through space, however, gives complete information, and from this can be predicted the directivity and other interesting properties of a given aerial.

In order to achieve this result, the aerial is assumed to be at the centre of a large sphere, and a study is made of the amount of power flowing through each area on the sphere. From these data, contour lines of equal intensity can be plotted and projected on to a plane in such a manner that equal areas on the sphere are represented by equal areas on the plane of projection.

Several methods of projecting the surface of a sphere exist; the most convenient, however, for illustrating the polar distribution over a hemisphere consists in drawing lines of latitude as equally spaced parallel horizontal lines on the plane, and calculating the equation giving the law for longitudes on the plane. This is a cosine law, and results in an "onion" shaped projection of the hemisphere. (The hemisphere under consideration is that which faces and is behind an observer situated at the foot of the array and looking in the direction of radiation.)

A convenient figure to indicate the directivity of an aerial is the ratio of the powers supplied respectively to a non-directional aerial, assumed ideally to be a point source, and to a directional aerial in order to obtain equal field intensities at a distant point in the most favoured direction of the directional aerial.

The method used for calculating the power distribution from an aerial was as follows:—

From the classical expression giving the field intensity at a distant point due to a single $\frac{1}{2}\lambda$ dipole, the field due to an aerial may be calculated in terms of latitude and longitude. Successive longitudinal cuts are made through the sphere, and a series of values are given to the latitude. Similarly, cuts are made through the sphere at various latitudes, and a series of values are given to the longitude. From these data the contour lines for 90 % power, 80 % power, etc., can be plotted on the projection of the sphere, and by means of a planimeter the enclosed surface and the total area are evaluated. The "directivity" is given by the expression

$$\frac{A \cdot P_m}{\Sigma \cdot P \cdot \delta A}$$

where A is the total area of the sphere, P_m the maximum power (100 %), P any power contour line, and δA the area enclosed by this contour line.

The calculations were limited to the consideration

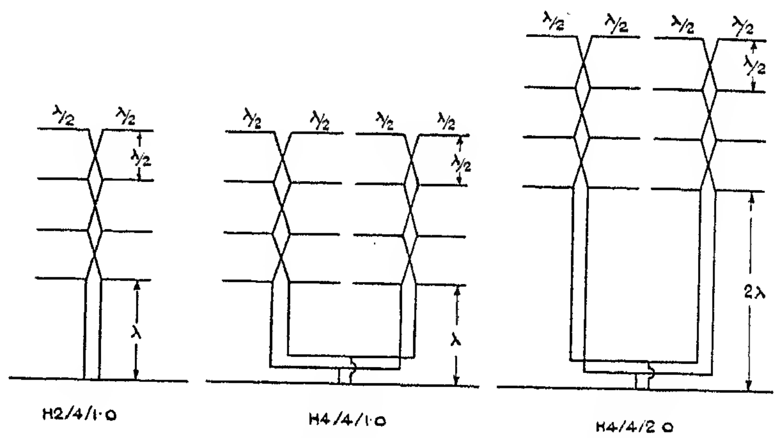


Fig. 7.—Types of aerials used at Daventry.

of directional aerials composed of horizontal dipoles, which, as a result of experiment, it had been decided to use. The form of the aerials considered is shown in Fig. 7, given respectively the designations H2/4/1, H4/4/1, and H4/4/2. In this designation the first letter indicates the type of aerial (horizontal or vertical), the first figure the number of $\frac{1}{2}\lambda$ dipoles in the horizontal plane, the second figure the number of elements in the vertical plane, and the third figure the height above the earth (in wavelengths) of the bottom dipole. Figs. 8, 9, and 10, give the theoretical power distribution diagrams for forward radiation from three types of aerial used, and Table 2 summarizes the theoretical directivity of the same three types, both with and without reflectors. Fig. 11

Table 2

THEORETICAL DIRECTIVITY OF AERIALS USED AT DAVENTRY

Aerial type	Directivity*	Width of main longitudinal lobe for 25 % power (signal 6 db. down)	Latitude of main lobe (projection angle)
H2/4/1·0	42	± 34°	7·8°
HR2/4/1·0	77·7	± 34°	7·8°
H4/4/1·0	80	± 18°	7·8°
HR4/4/1·0	148	± 18°	7·8°
H4/4/2·0	100	± 18°	5·0°
HR4/4/2·0	185	± 18°	5·0°

* Ratio of powers to be supplied respectively to a hypothetical aerial radiating uniformly in all directions, and to a directive aerial in order to obtain equal field intensities at a distant point in the most favoured direction of the directive aerial. Reflector assumed 85 % efficient in forward direction.

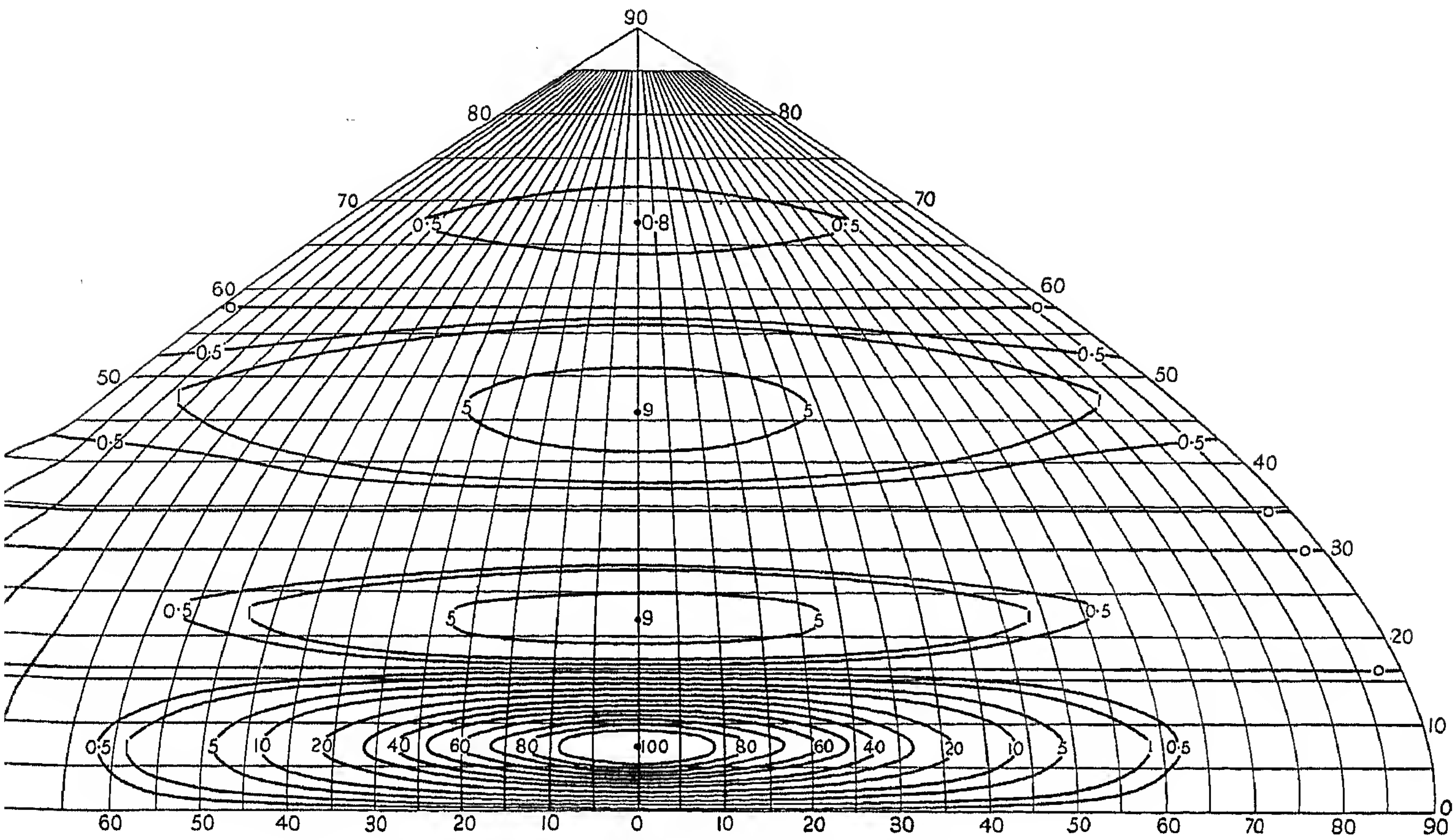


Fig. 8 —Power distribution diagram—aerial type H2/4/1.

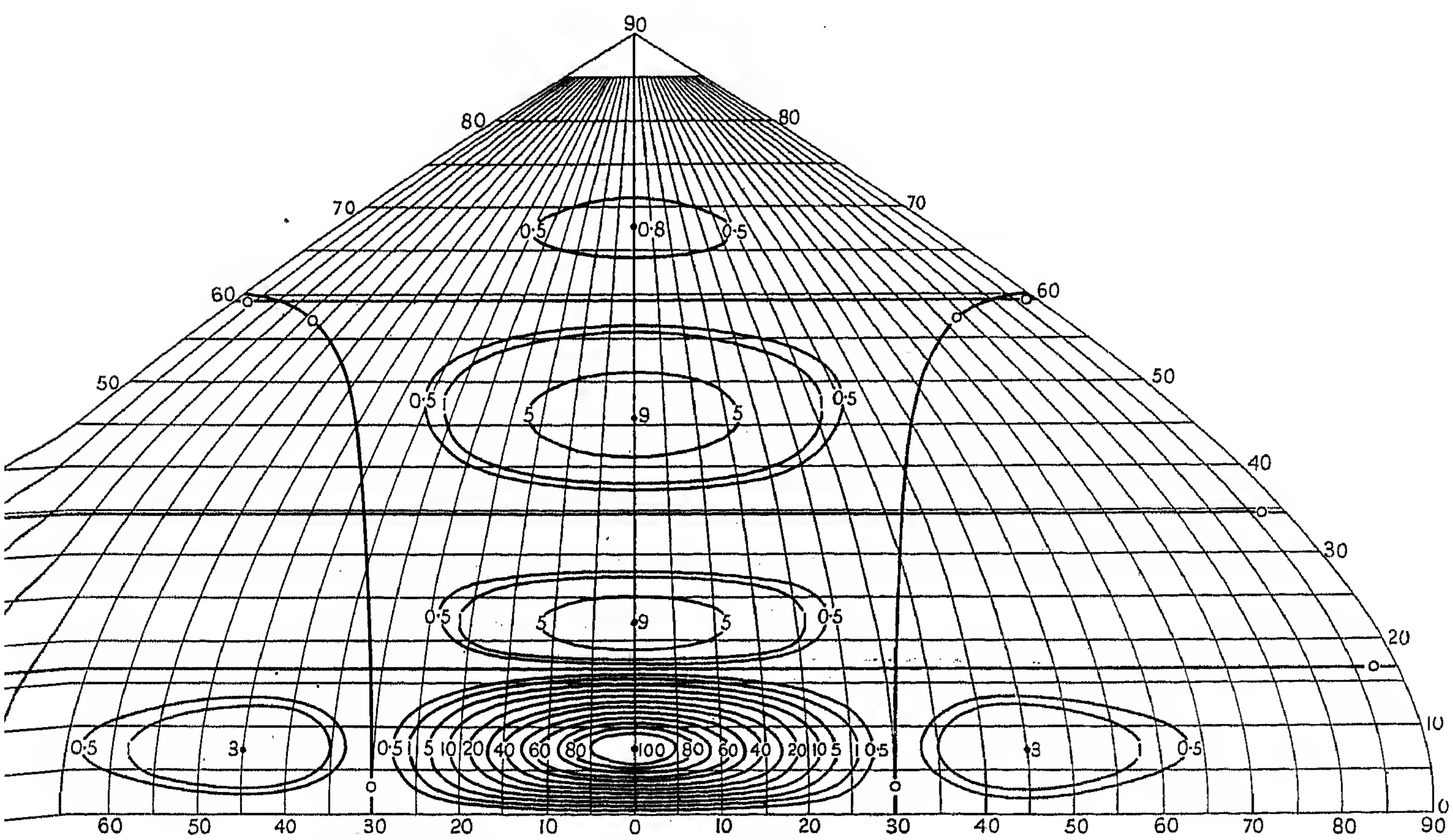


Fig. 9.—Power distribution diagram—aerial type H4/4/1

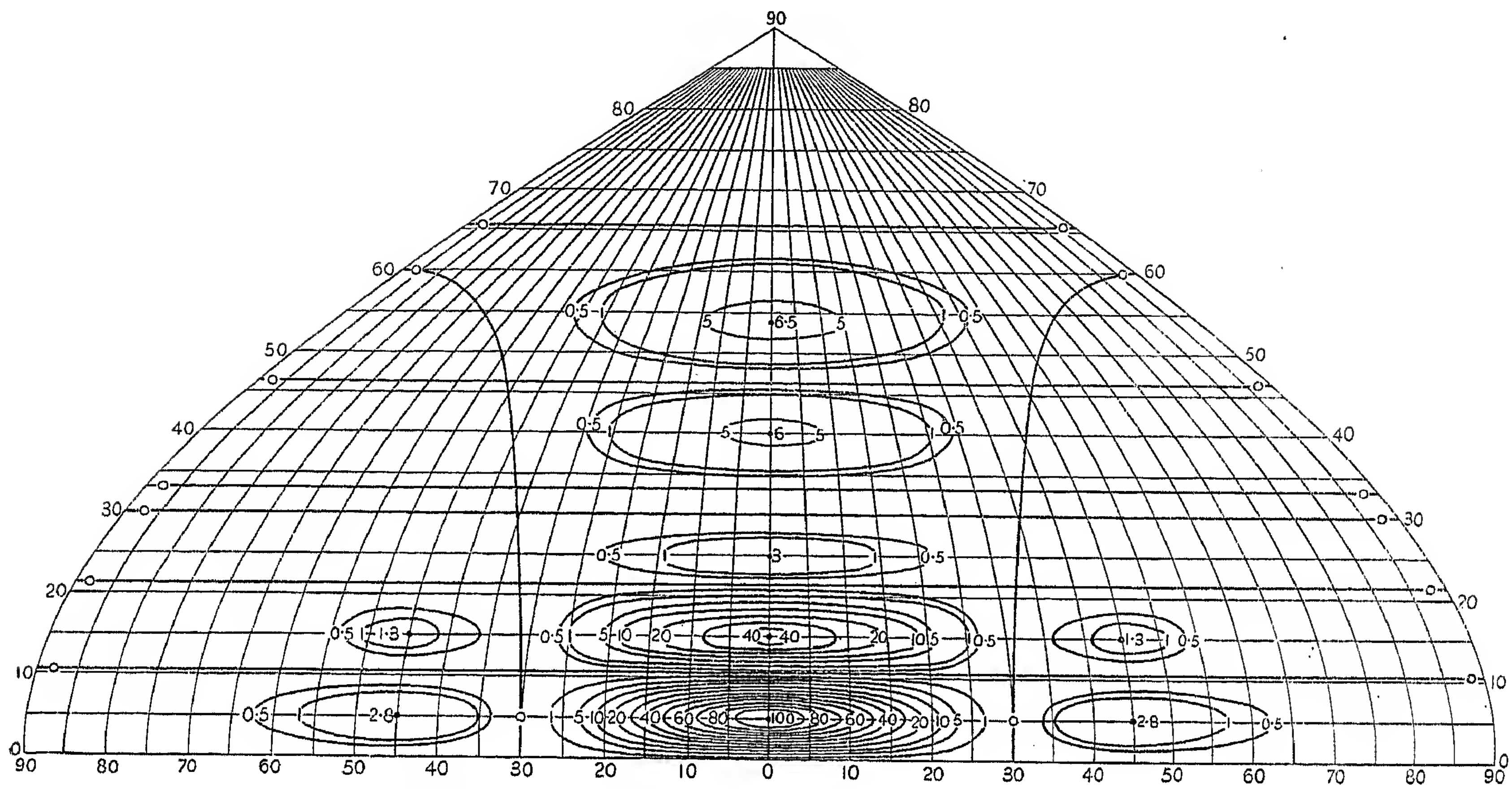


Fig. 10.—Power distribution diagram—aerial type H4/4/2.

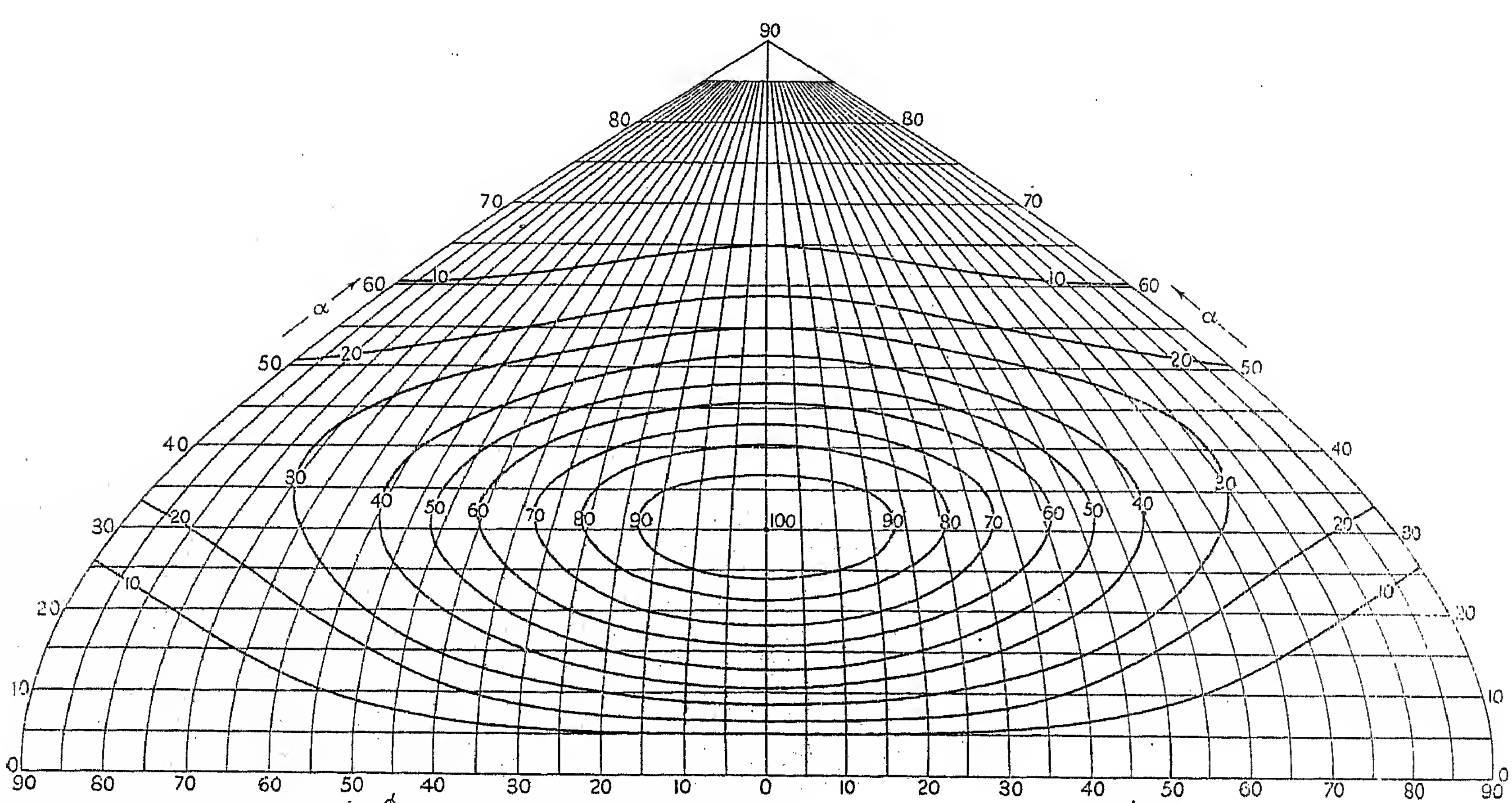


Fig. 11.—Power distribution diagram—aerial type H1/1/0·5.

gives a similar diagram for a $\frac{1}{2}\lambda$ dipole $\frac{1}{2}\lambda$ above the ground (H1/1/0·5) for purposes of comparison.

The directivity of the usual standard comparison aerial, a $\frac{1}{2}\lambda$ horizontal dipole $\frac{1}{2}\lambda$ above the ground, is 6·6 (see power distribution diagram in Fig. 11).

(c) Back Radiation from Aerials

Nearly all the aerials erected at Daventry are provided with reflectors, with a consequent gain of nearly 3 db. in the forward radiation. Another very important property of a reflector is that of eliminating back echo at the distant receiver; this echo is due to the difference between the distances travelled by the forward wave and the back wave (with no reflector) in opposite directions round a great circle.

Since a parasitic reflector is not a perfect reflecting surface and has an efficiency of the order of 85 %, a small amount of power is radiated in the backward direction. This is not generally sufficient to cause prominent echo and is indeed not a disadvantage since it enables some service to be given in directions 180° from the main direction of transmission. In this way, as an example, the West Indies, bearing 260° E. of Daventry, obtain some service at local breakfast time during Transmission 2, which is directed on 80° E. of Daventry for evening reception in Malaya and India, the wavelengths of 14 m. and 17 m. used being suitable for propagation in both directions.

(d) Practical Design of Aerials

The design of aerials capable of operation at a power input of 100 kW did not present any difficulty, assuming reasonable precautions to ensure a uniform power distribution in all the elements in the aerial.

The design of the insulators supporting the dipoles, and the gauge of conductor from which the dipoles were to be formed, were the first two points to be settled, as these factors governed the design of the aerial system from the mechanical point of view.

The type of insulator had first to be decided because their capacitance influenced the length of the dipole conductor. Further, the loss in the insulators was a matter of importance. The only type of insulator suitable for this purpose is the rod type, and laboratory experiments were conducted on insulators of this type, having net lengths of 4, 8, 12, and $16\frac{1}{2}$ in. Sample insulators were fitted with corona rings of various sizes, and the temperature-rise was measured at voltages up to 20 000 at frequencies covering the operating waveband. Space does not permit reproduction of the detailed results of these experiments, but the insulator finally used has a length of 8 in., a diameter of 1 in., and is fitted with corona rings as illustrated in Fig. 12. This insulator has a capacitance of approximately 1 $\mu\mu$F between corona rings.

In practice the insulators are subjected to a carrier voltage of approximately 7·5 kV (r.m.s.). At the point of maximum heating, which is near the high-potential corona ring, the temperature-rise at this voltage was found to be 11 deg. C. It was proved that a slightly lower and more uniform temperature-rise throughout the length of the insulator could be obtained by the use of corona rings having a diameter of 5 in., but the greater capacitance of this size of ring made its use inadvisable.

The type of insulator having been determined, the length of the dipoles for each operating wavelength was obtained experimentally. In final form these consisted of No. 12 gauge cadmium copper wire, having a physical length of approximately 0·45 λ.

The system of feeding the vertically spaced dipoles in pairs by means of a feeder connected to the high-potential ends of adjacent dipoles, which was extensively used on the experimental aerials, was confirmed. With 4 dipoles in the vertical stack this system produces an impedance of 500 to 900 ohms at the base of the feeders. Since there are two feeders to the driver curtain of each aerial, which must be fed in parallel and, in the case of unslewed aerials, in phase, it is apparent that the transmitter feeder must have an impedance equal to half that of the aerial feeders if direct connection be used.

To ensure that all 4 dipoles in a vertical stack were fed in phase, experiments were undertaken to determine the wave velocity along the vertical feeders. The presence of the $16\frac{1}{2}$-in. rod insulators used to space the feeders resulted in a reduction in velocity, and experiments were undertaken to determine the correct spacing of the horizontal stacks for each operating wavelength.

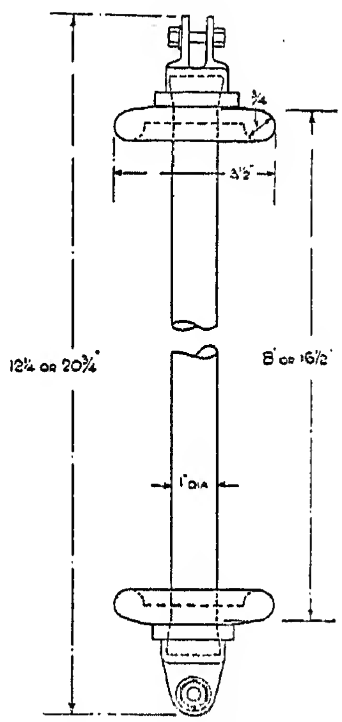


Fig. 12.—Type of insulator used on aerials and feeder lines.

In order to compensate for the 180° phase shift on the feeders between each pair of dipoles, it was decided to twist the feeder on itself. This arrangement, while not quite so reliable mechanically as one involving an abrupt cross-over at a definite point, nevertheless possessed the advantage of obviating impedance discontinuities. In practice no mechanical difficulties due to this form of construction have been experienced. The actual design of a typical aerial is shown in Fig. 13.

The straining wires which are used to support and maintain tension on the dipoles consist of $\frac{7}{8}$ in. and $\frac{7}{16}$ in. circular galvanized steel-wire rope and are broken up with small walnut insulators. They are secured at the top end to the spreaders, the lower end being taken to

rod-and-plate anchors. The downcoming feeders from each pair of dipoles are anchored solidly to the ground by means of short-circuited quarter-wavelengths of feeder attached to rod-and-plate anchors. This arrangement has the advantage of providing a direct connection to earth for lightning discharges.

Since both the downcoming feeders and the rigging wires were secured solidly to the ground, it was necessary to provide some means of compensating for excessive wind loading. In the past it has usually been the practice to secure these members to the ground through the medium of counter weights, but this system could not be adopted in this particular case owing to the complex arrangement of feeders to which the aerial feeders were coupled. It was therefore decided to provide counterweights in the main halyards, and to this end concrete weights were provided at the base of each 325-ft. mast.

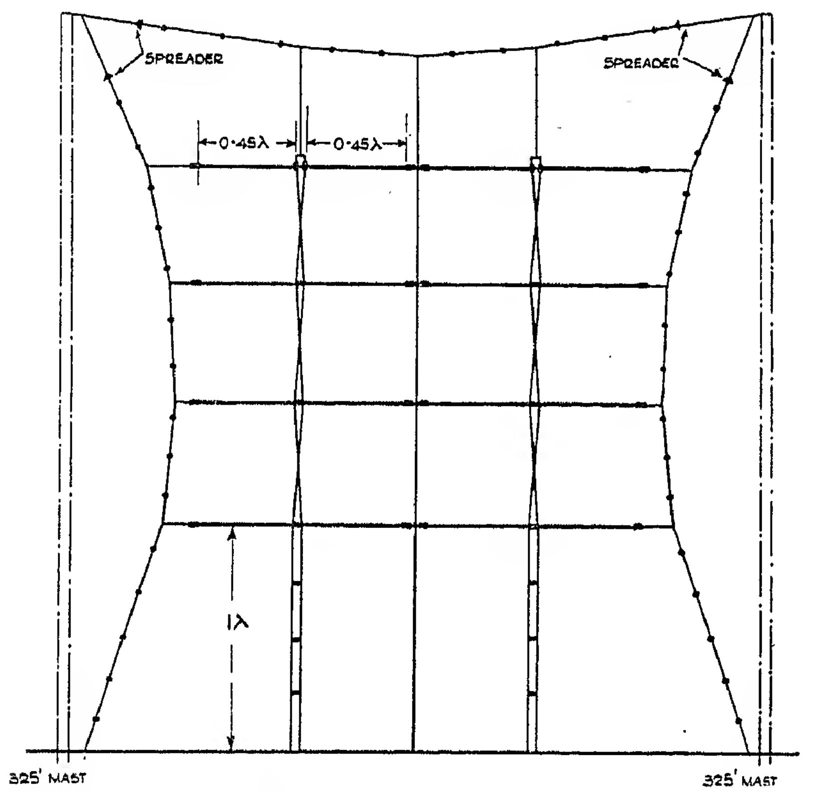


Fig. 13.—Typical aerial.

These blocks are supported in vertical guides and joined to the main halyard through suitable tackle.

This system has proved to be satisfactory. The number of breakages to date has been insignificant and can easily be attributable to some definite cause such as damage to the dipole conductors during erection.

(e) Design of Masts

The exact method of supporting and applying tension to the aerials was to a large extent bound up with the design of the masts. A preliminary investigation showed that it would be economical to sling two or three aerials between each pair of masts. The following schemes were considered:—

(*a*) In which each curtain of each aerial is suspended from an independent triatic supported from cross-arms fixed rigidly to the mast structure, the necessary tension being applied to the dipoles by means of horizontal straining wires taken from the ends of the dipole insulators to fixing points at appropriate heights on the mast or by means of rigging wires stretched between the mast head and ground anchors.

(*b*) In which all aerials between two masts are carried on two triatics only, supported on fixed cross-arms, the horizontal tension being applied by one of the two methods mentioned under (*a*).

(*c*) In which all aerials between any two masts are carried on two triatics only, spaced by spreaders of appropriate length which are free to swivel independently.

Scheme (*c*) was chosen because calculations showed that this arrangement imposed the smallest load on the masts and had the advantage that it did not subject the structure to the torsional stresses which would be set up by fixed cross-arms.

The arrangement chosen suffers from the disadvantage that all aerials supported between any two masts must be raised and lowered simultaneously, but the operating personnel expressed the view that no difficulty would be encountered, and experience has proved this to be the case. Trial rigs were worked out and it was found that one 25-m. and one 31-m. aerial of the type described, with reflectors, could be supported between a pair of 325-ft. masts spaced 650 ft., the triatic sag being of the order of 40 ft. This arrangement imposed a load on the mast head of 5 tons horizontally, at a wind velocity of 70 m.p.h. The use of counterbalance weights in the halyards prevents the halyard tension exceeding this figure.

The loading condition for one 14-m., one 17-m., and one 19-m. aerial between masts of similar height and spacing was investigated and found to be approximately 5 tons with a triatic sag of 50 ft.

Loadings on masts having heights greater and less than 325 ft., were also investigated, but it was proved that this height was the most economical. The height and loading at the mast head having been determined, the question of the type of mast had next to be considered. The decision not to use fixed cross-heads made it possible to consider the use of stayed masts, and, although masts of this type have seldom been used for the purpose of supporting short-wave aerials, the designers could not discover valid reasons why this type should not be used, provided the stays were arranged in such a manner that resonant lengths did not mask the active portions of the aerials.

This type proved to be the cheaper, and it was decided to adopt it.

The masts as erected are of the uniform-section lattice type, supported by three or four sets of stays, the arrangement of stays varying with their position in the system.

Plate 1 (facing page 336) shows a perspective view of three aerials each with a reflector suspended between two masts.

The main supporting triatics are broken up with insulators in every case where a dipole is within $0\cdot5\,\lambda$ of the triatic. The triatics consist of $2\frac{1}{4}$-in. circumference steel-wire rope, and the insulators are $6\frac{5}{8}$-in. walnut type.

The scheme adopted necessitated the use of a large number of spreaders, and, since some of these were inserted towards the centre of the triatic or midway between two aerials, it was essential to keep the weight to a

minimum. The spreaders used are of the welded lattice steel type constructed with steel tube $1\frac{1}{4}$ in. outside diameter and No. 18 S.W.G. wall thickness. This method of construction produces a very strong spreader of remarkably light weight. For example, one of the 21-ft. spreaders weighs only 70 lb. and is capable of withstanding a compressional load of 30 cwt.

The aerials required are set out in Table 3.

It will be observed that the aerials have been arranged in such a manner as to bring those which were to be operated at short wavelengths to the end of the system, which, owing to the closer vertical spacing between dipoles, permitted the use of 250-ft. and 150-ft. masts. This arrangement resulted in the longest feeder runs to aerials operating at the shortest wavelengths, but tests have proved that the loss is not excessive. In the case of

Table 3

Description of Aerials at Daventry (as on 26th May, 1938)

Aerial number	Working on	Designed wave, in metres	Bearings, in degrees (E. of N.)	Reflector*	Number of horizontal half-wave elements	Number of vertical stacks	Height of bottom stack above earth (in wavelengths)
1	GSG	16·863	294	R	4	4	1
2	GST	13·973	294	R	4	4	1
3	GSP	19·595	294/114	RR	4	4	1
4	GSD	25·532	294/114	RR	4	4	1
5	GSC	31·315	294/114	RR	4	4	1
6	GSG	16·863	80/260	RR	4	4	2
7	GSJ	13·934	80/260	RR	4	4	2
8	GSF	19·815	80/260 and 68/248	RR Slewable	4	4	2
9	GSB	31·545	80/260 and 92/248	None Slewable	4	4	1
10	GSD	25·424	80/260 and 92/248 and 68/272	None Slewable	4	4	1
11†	GSA	49·59	80/260	None	4	2	1
12	GSD	25·380	42/222	None	4	4	1·5
13	GSD	31·315	42/222	None	4	4	1
14	GSO	19·763	42/222	RR	4	4	2
15	GST	13·973	42/222	RR	4	4	2
16	GSD	25·532	160/324	RR Slewable	4	4	1·5
17	GSB	31·545	160/324	RR Slewable	4	4	1
18	GSG	16·863	44/224	RR	4	4	2
19	GSG	16·863	160/340	RR	2	4	1
20	GSI	19·659	175	R	4	4	1
21	GSB	31·315	126/306	None	4	4	1
22	GSL	49·10	126/306	None	4	4	1
23	GSH	13·973	160/340	RR	2	4	1
24	GSJ	13·934	80/260	None	4	4	1
25	GSI	19·659	135/315	RR	4	4	1

* RR means reversible reflector. R means non-reversible reflector. † Not erected.

The layout of the masts to support these aerials had to be made to conform to the plan of the land available and, if possible, to incorporate masts which already existed on the site. A plan of the site is shown in Fig. 14.

Masts A, B, N, and M existed. Masts A and B are self-supporting towers, having a height of 350 ft., while masts N and M have a height of 500 ft. and are of the uniform-section lattice stayed type. The height and spacing of the masts, the bearings on which the various aerials are orientated, and the territories which they serve, are marked on the plan.

a feeder having a length of 3 000 ft., the power measured at the aerial was 67 % of the transmitter output at 17 790 kc./sec.

The power loss in this feeder was measured by the method described by T. Walmsley.*

The following new masts were constructed:—

Masts	Height (feet)	No. of sets of stays
3	325	4
2	325	3
2	250	3
1	150	3

* *Journal I.E.E.*, 1931, vol. 69, p. 299.

All the above masts were designed for a horizontal head load of 6 tons. The necessity for constructing some masts with three and others with four sets of stays can be seen by reference to the plan.

It will be observed that the stays do not mask any of the active portions of the aerials; it should be remembered that, although the stay blocks are in front of some of the aerials, the stays are at this point on a much lower level than the radiators.

The mast bases were earthed to buried plates and the stays were not insulated, since it was impossible to choose a section length which would not resonate at some frequency within the operating range.

It will be seen that the layout developed was reasonably economical in that the maximum use was made of the masts, and it had the advantage that one aerial did not mask another. Had every aerial on the site operated on a different wavelength then the latter point would not have been of importance, but many of the aerials are constructed to operate on the same wavelength and the designers had to bear this fact in mind, also that the operating wavelengths of certain aerials might be changed in the future.

The layout of the aerials relative to the position of the building and the feeder runs had also to be considered. In the majority of cases it will be noted that a fairly clear run for the feeders is provided.

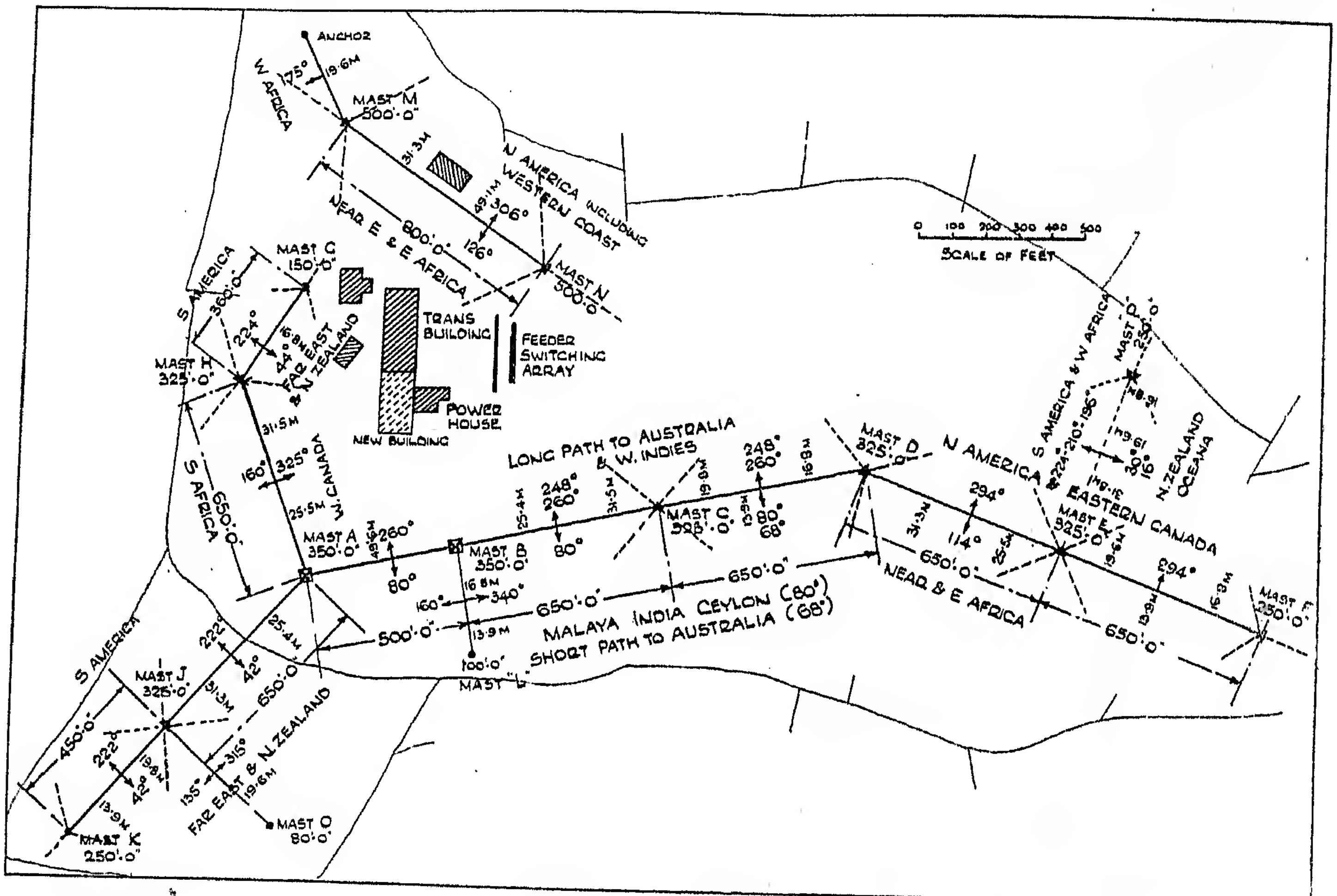


Fig. 14.—Site plan.

(5) FEEDER SYSTEM

(a) Design Considerations

The design of a feeder system to couple 25 aerials to 6 transmitters presented a problem of some complexity. The designers had to consider not only the electrical and mechanical design of the feeder lines as a means of coupling the transmitters and aerials, but also the provision of a switching system which would permit a ready means of interchange between the transmitters and aerials. The design of the feeders was therefore closely connected with that of the switching system.

Three types of feeder were considered:—

(i) Open-wire line (twin or 4-wire).
(ii) Concentric tube.
(iii) Busbar.

The balanced open-wire type of feeder is simple and cheap to construct, easy to repair, and can be dismantled and re-erected at small cost. If carefully designed, it is equal in efficiency to any other type. Furthermore, switching is a relatively simple matter.

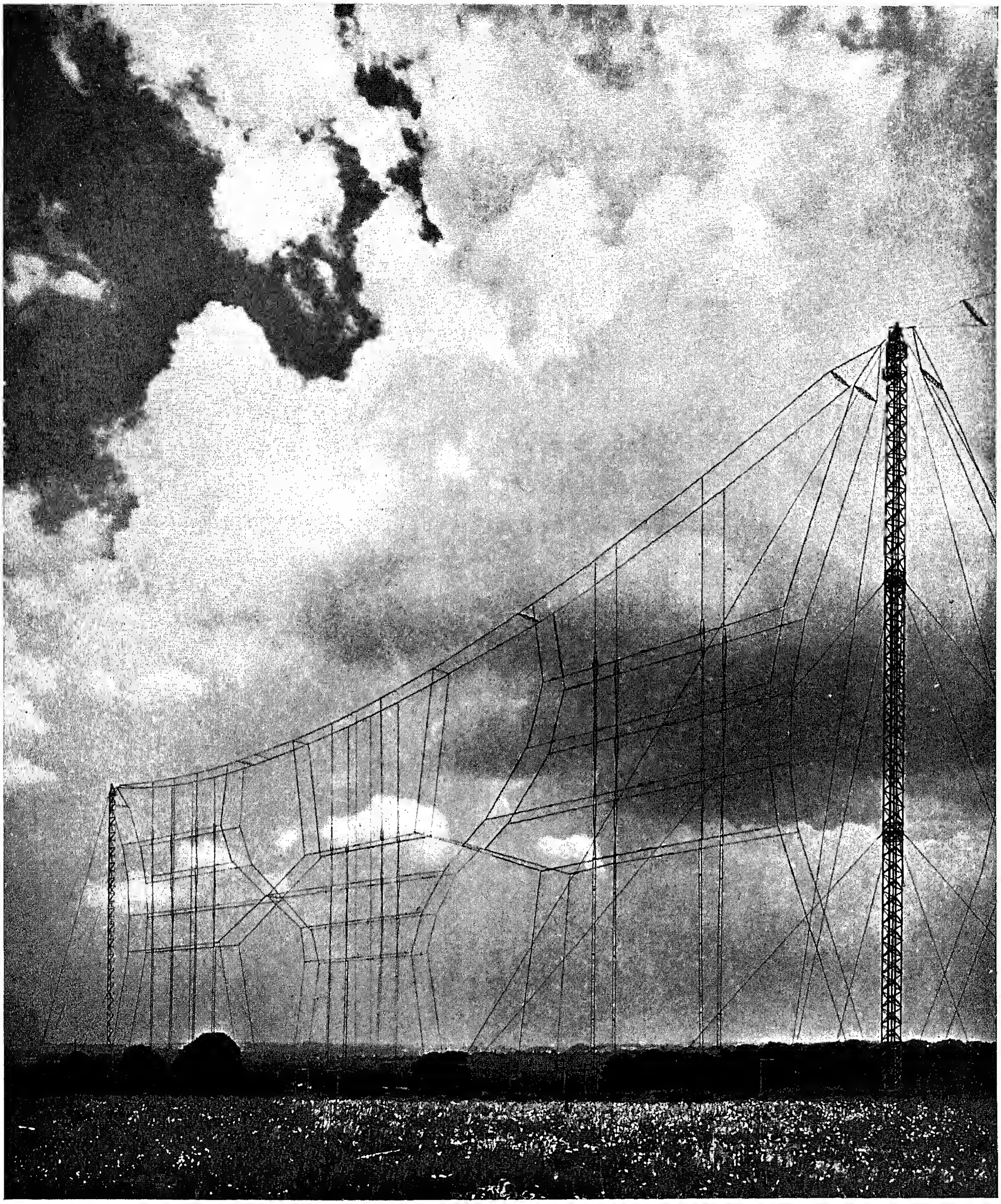
Against these advantages, it is affected by lightning, its characteristics tend to change with weather conditions, and it radiates if operated in an unbalanced condition.

The concentric-tube type of feeder has none of these disadvantages, and the electrical characteristics of a properly designed feeder are not affected by weather, but the cost of construction is high and skilled staff are required for installation or repair. The risk of serious damage by flashover, due to standing waves, although reduced by modern protective circuits, is greater than in the case of other types.

The greatest disadvantage of this type of feeder for the purpose under discussion, apart from its cost, is the difficulty and cost of designing simple and reliable switching systems.

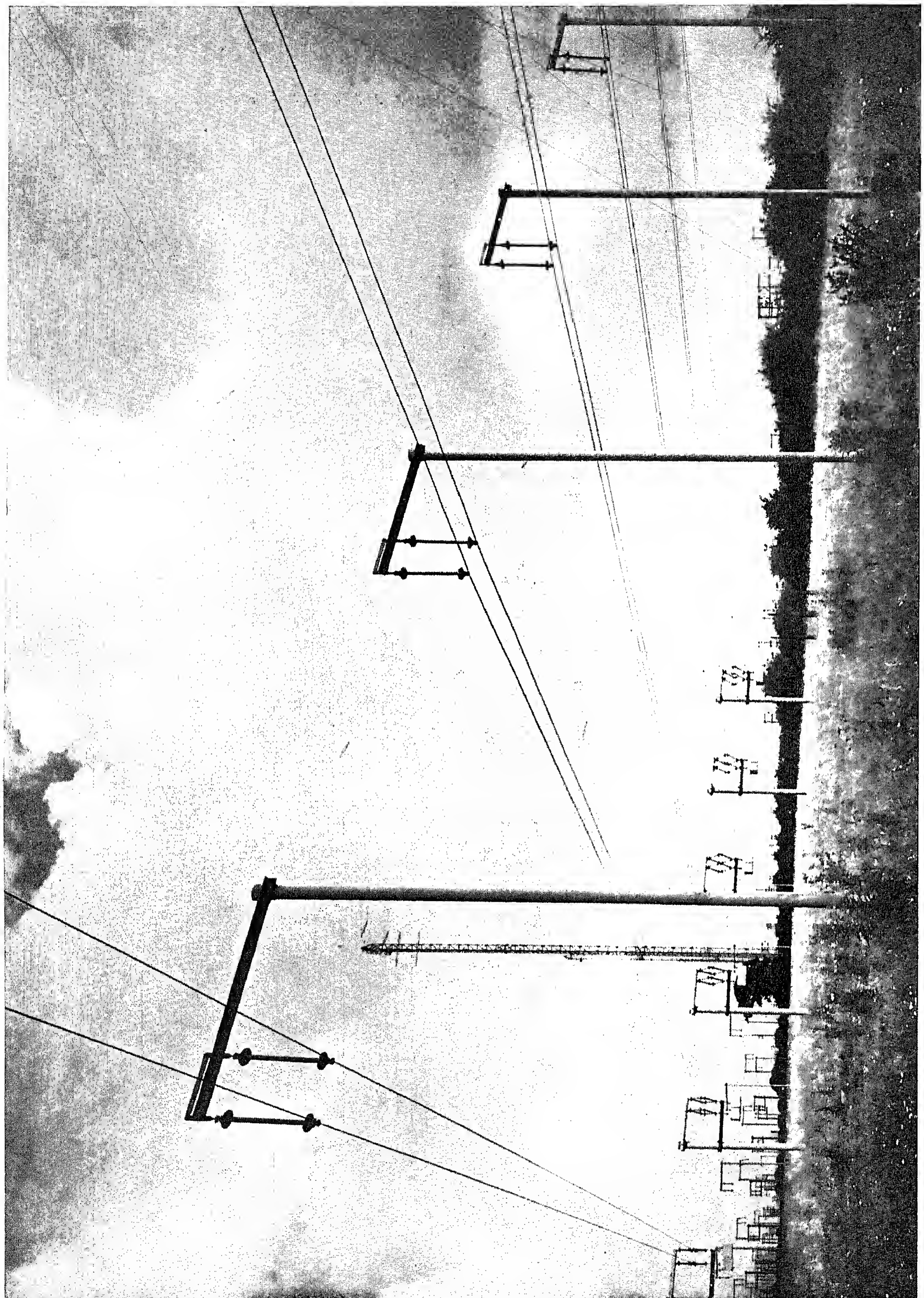
In an attempt to obtain the advantages of both types

Plate 1



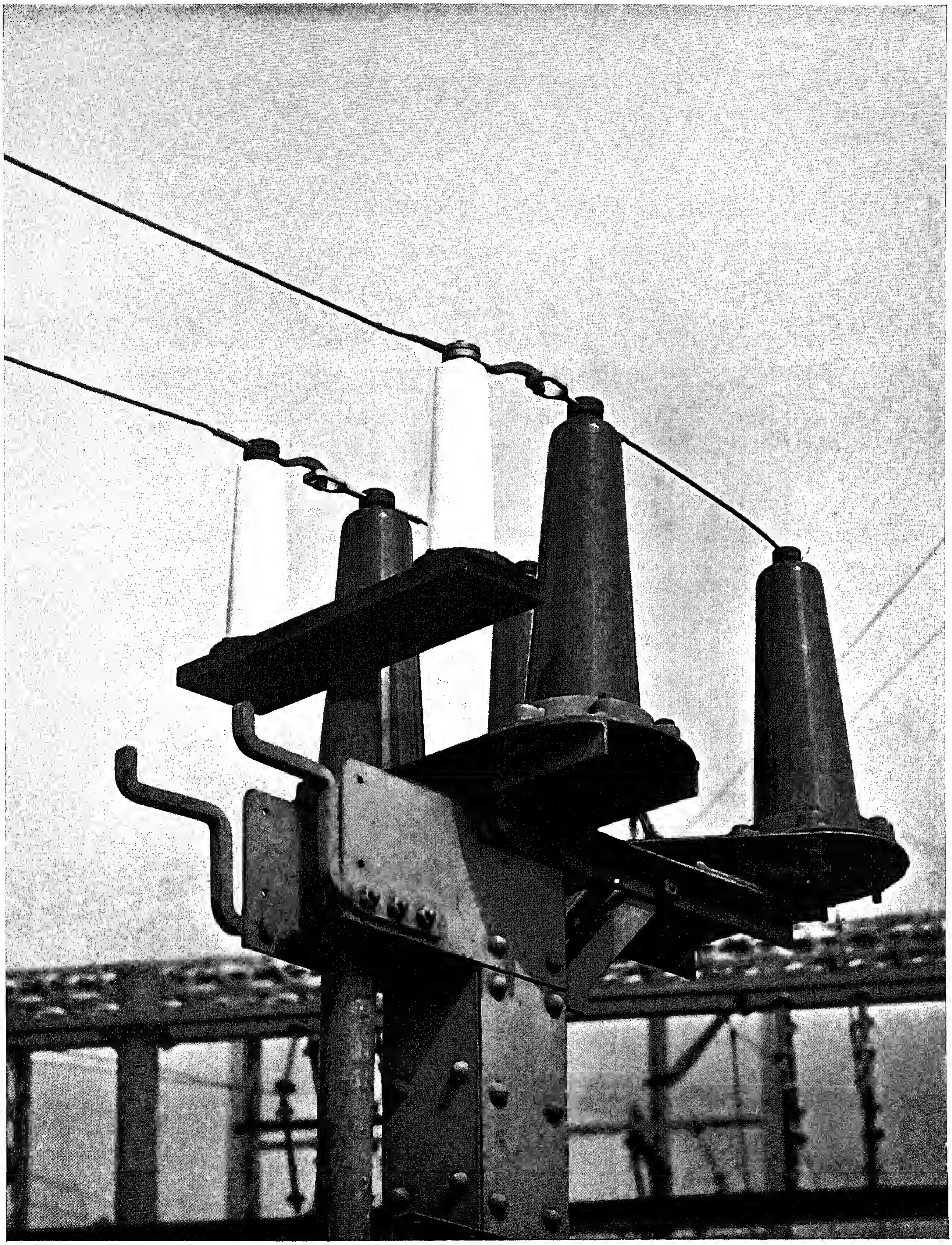
Perspective view of 3 aerials, each with a reflector, suspended between 2 masts.

Plate 2



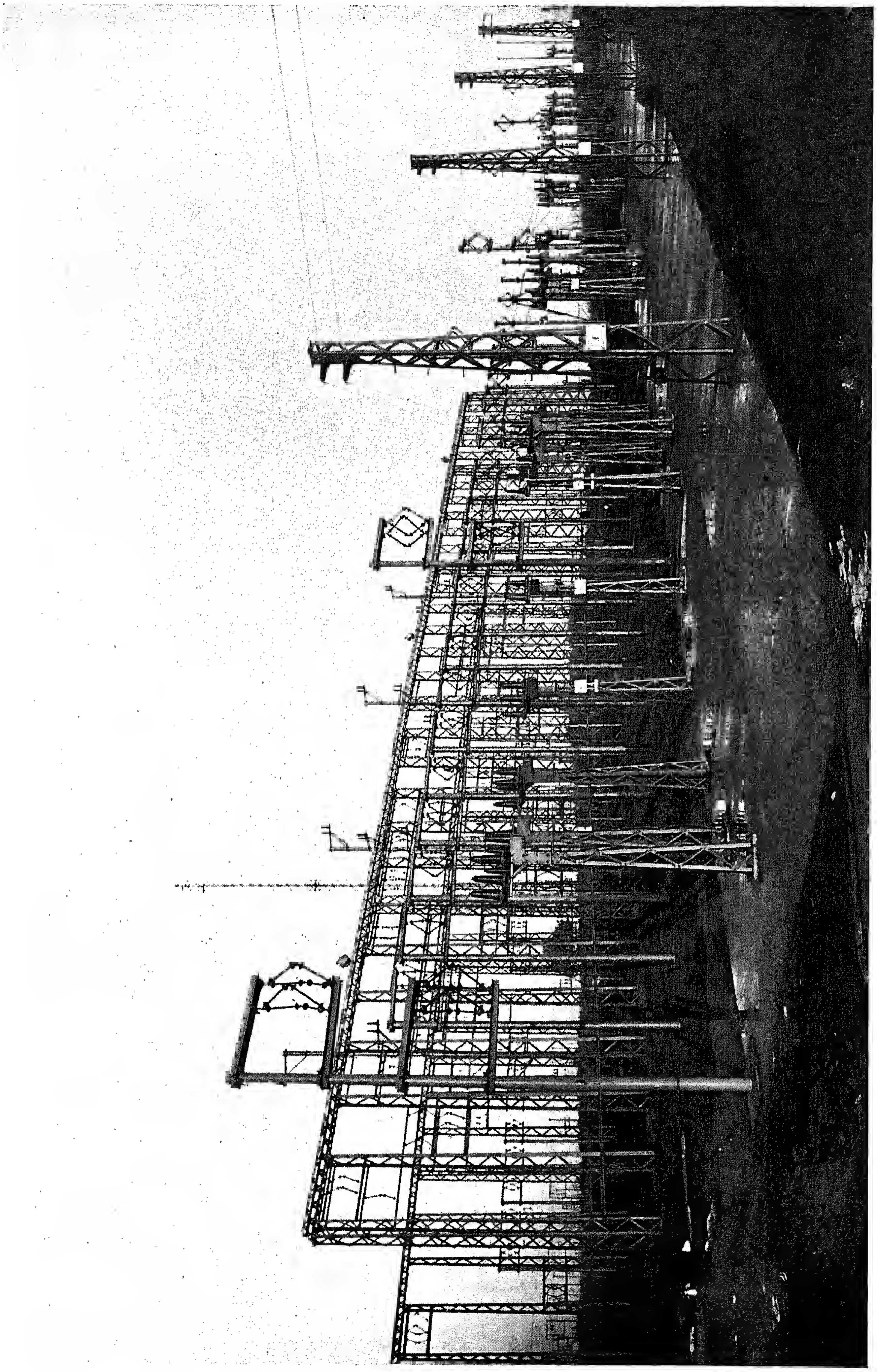
View of typical feeder run, showing suspension and tension sets.

Plate 3



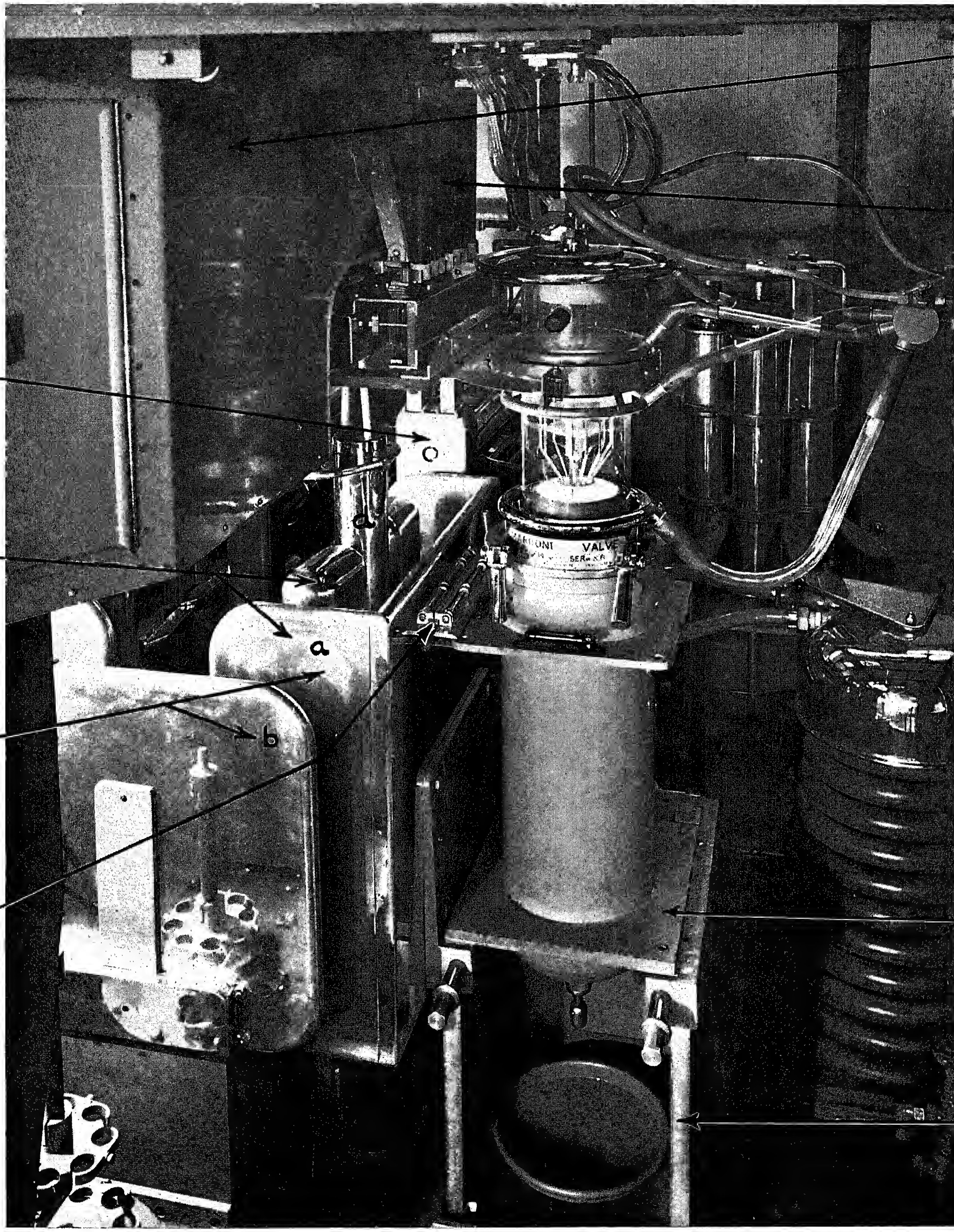
Constructional details of hook switch.

Plate 4



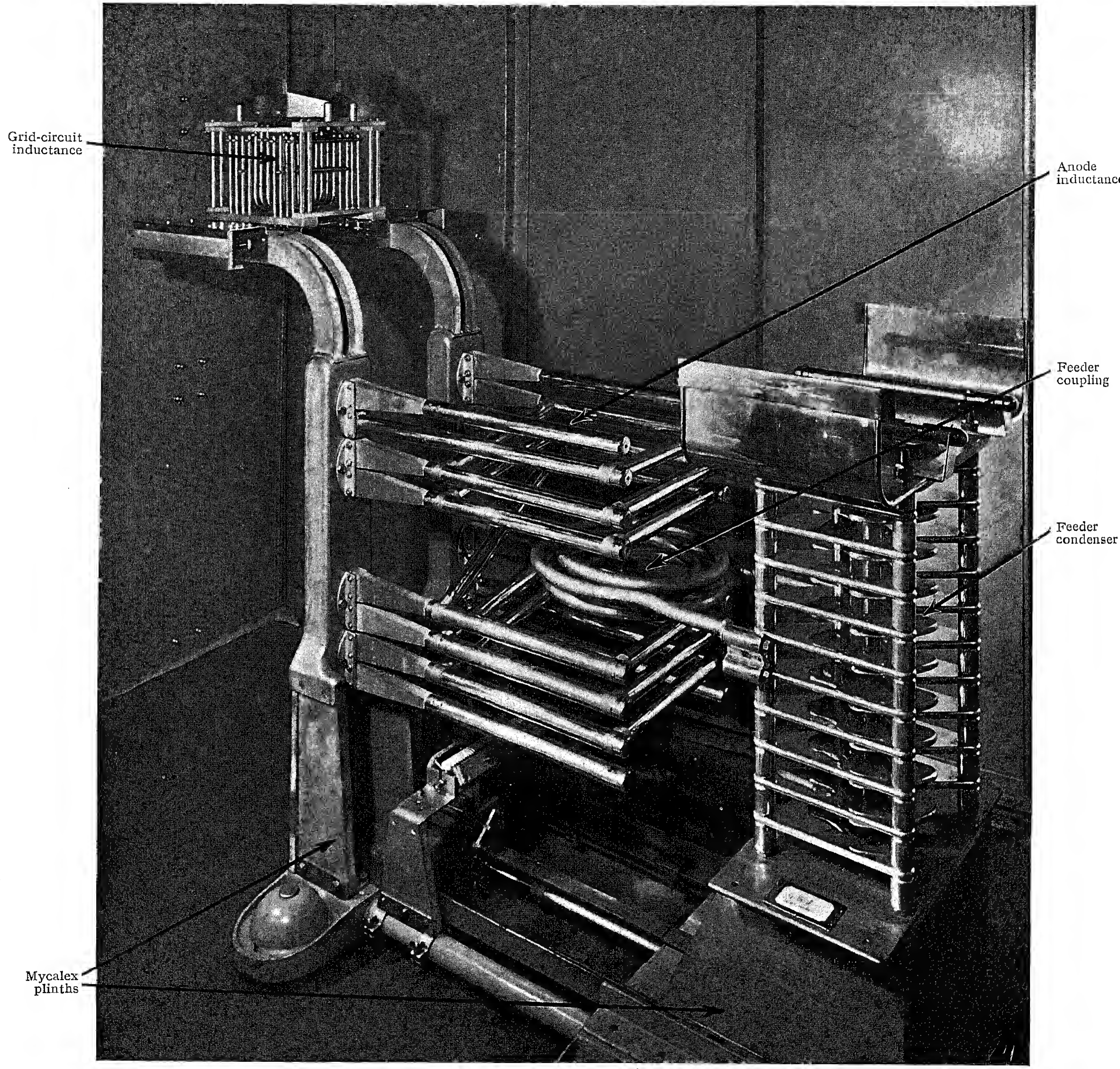
Main distribution frame, with selector switches in foreground.

Plate 5



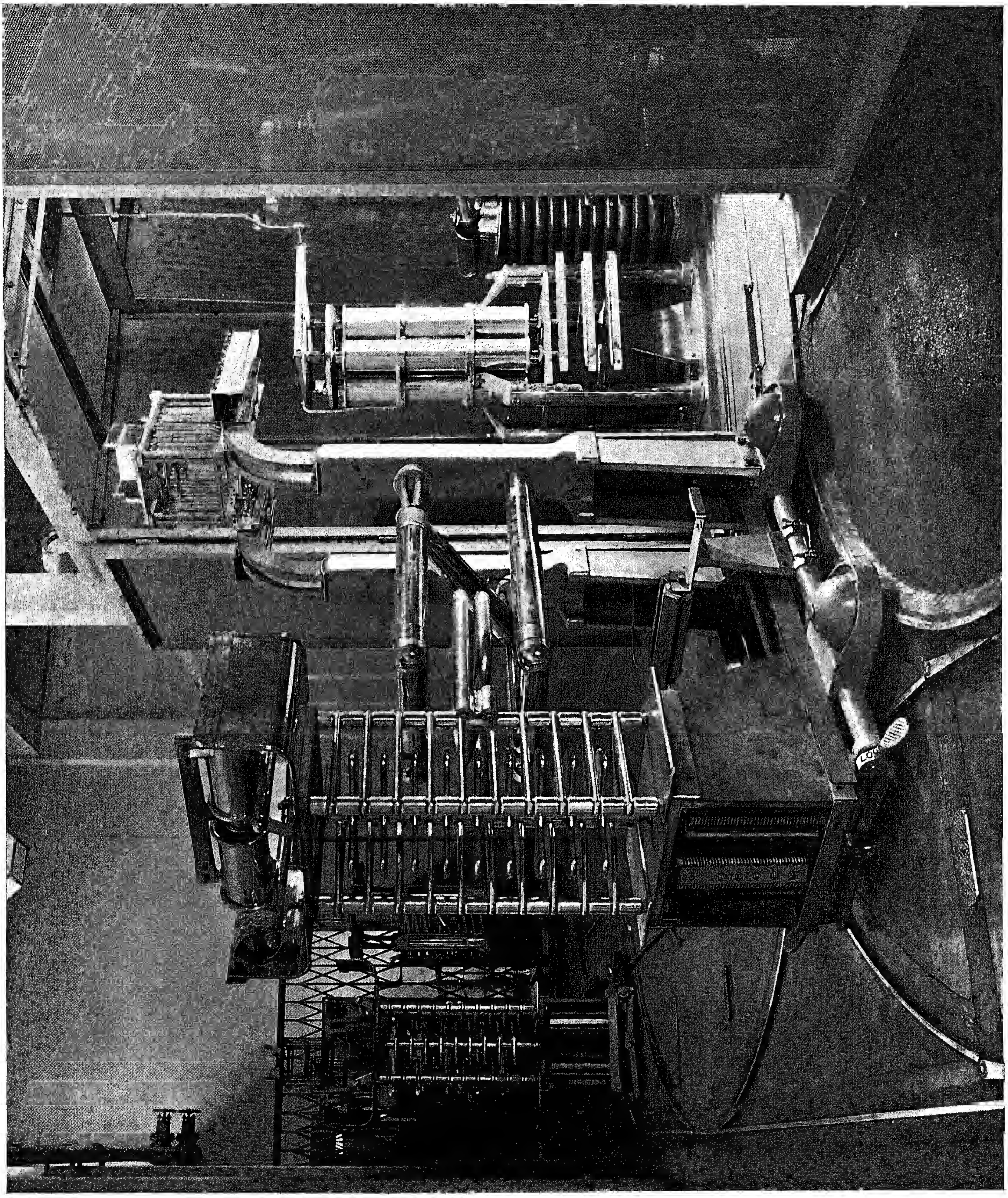
Marconi transmitter. Part of high-frequency amplifier.

Plate 6



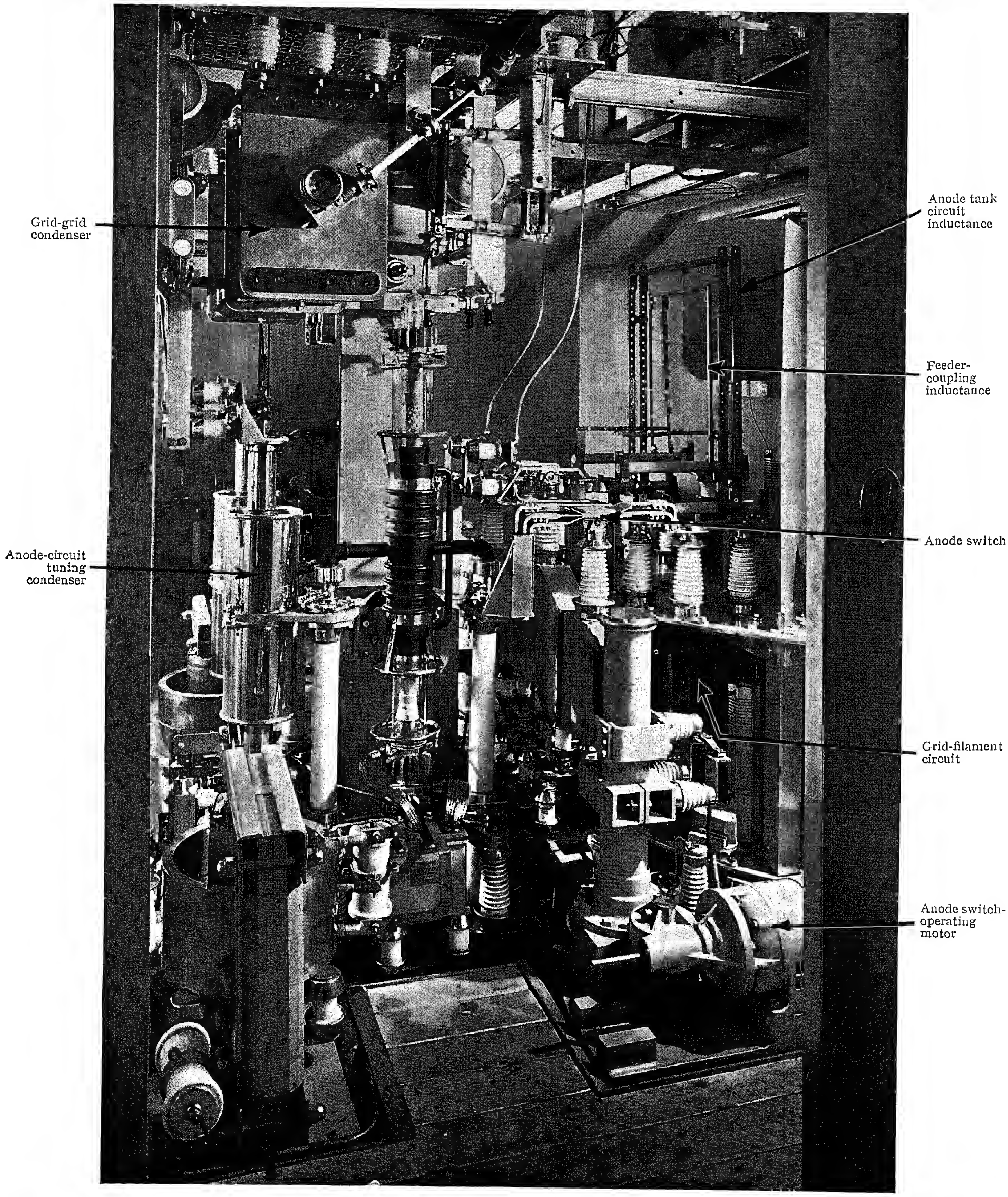
Marconi transmitter. Typical circuit truck for 49-m. wavelength.

Plate 7



Marconi transmitter. Typical circuit truck for 16-m. wavelength.

Plate 8



Standard transmitter. Part of main high-frequency amplifier.

of feeder an experimental length of open busbar was constructed. This consisted of two busbars of hollow section and of the dimensions shown in Fig. 15. This size of bar and spacing gave a characteristic impedance of approximately 275 ohms over the operating waveband and had a loss comparable with that of other types, but the close spacing necessary to obtain the required impedance precluded its use on a service station because it was found necessary to enclose the feeder to prevent short-circuiting by large insects, birds, and snow. The cost of an enclosure made the total cost equivalent to that of the concentric type.

When all factors were taken into consideration, it appeared that the open-wire type of feeder was suitable for this particular purpose. Nevertheless, the concentric type is preferred and is used in cases where the feeders

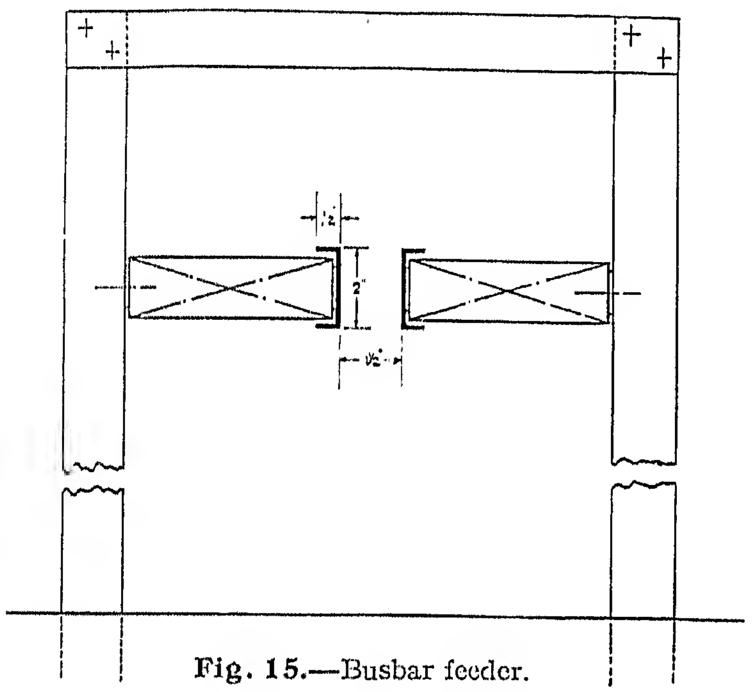


Fig. 15.—Busbar feeder.

are short and the transmitters are permanently coupled to aerials which require an unbalanced feed.

Experimental lengths of open-wire feeders were constructed. In order to maintain an adequate factor of safety and to allow for the possibility of the transmitters being worked at their maximum output, it was decided that the feeders must have an adequate factor of safety when transmitting a carrier power of 100 kW modulated to 100 %.

The open-wire feeder as originally designed consisted of No. 6 S.W.G. hard-drawn copper wire, spaced 12 in. between conductors and supported by insulators of a design similar to those used in the aerials, except that the length of the porcelain was increased to 16½ in. Experiments had proved that the use of any other type of insulator was inadvisable. The lines were supported on steel poles of sufficient height to give a minimum clearance between conductor and ground of 10 ft. Steel brackets were bolted on one side of the pole only, this arrangement being adopted to avoid introducing the capacitance of the pole between conductors. A view of a typical feeder run, showing suspension and tension sets, is given in Plate 2. The supporting poles were spaced at distances of 80 ft.

In the design of such a line it is of course essential to keep the capacitance of corona rings and other fittings to a minimum in order to prevent appreciable capacitance reactance across the lines at these points. Further, the diameter of the conductor must be sufficient to prevent loss due to corona discharges.

Considering the first point, it is difficult to design a twin-wire line, capable of transmitting the power required, which does not possess discontinuities of impedance, and this is clearly demonstrated by the results which were obtained on an experimental line having a length of 940 ft. The characteristic impedance of this line, calculated from its physical constants, was 580 ohms. The line, when terminated by a resistance of 562 ohms at its distal end, gave the following impedances at the proximal end:—

λ	R_s	X_s
m	Ω	Ω
14	490	− 157·3
15	845	+ 261
16·5	197·5	+ 127·8
20	322	+ 76·5
25	544	− 388
30·5	580	− 16
47·5	840	+ 1 680

It was apparent that the capacitance of the corona rings and insulator fittings was primarily responsible for the above result, but the relatively high peak voltages on these lines, which exceed 21 kV (assuming an entire absence of reflections), made it inadvisable to reduce the size of the corona rings.

It was also proved that, in cases where the reflection exceeded 15 %, corona discharges were set up from the lines at powers of about 100 kW at 100 % modulation.

Since the above lines were satisfactory for the transmission of 60 kW, at which power output to the feeder the transmitters would work in the immediate future and reflection could be neutralized by matching reactances placed at appropriate positions along the line, it was decided, in view of the shortness of time available for further experiments, design, and construction, to adopt twin-wire lines in the first instance. The mechanical construction adopted was of such a nature as to permit modification to the structure of the line at a later date. The energy loss in these lines as constructed was reasonably low; for example, a reasonably matched line having a length of 3 000 ft. gave an efficiency of 67 % at a frequency of 17 790 kc./sec.

Considerable operating experience has now been obtained in the use of these lines and it has been proved that, while the reflections due to lumped reactances across the line can be cancelled by reactances consisting of short lengths of feeder coupled to the line at appropriate points, the use of such methods is inconvenient and necessitates the expenditure of a considerable amount of time on the part of the operating staff. Experiments were therefore conducted with 4-wire lines spaced as shown in Fig. 16. Such a line has proved to be eminently satisfactory and, when supported by insulators of a type similar to those used on the twin-wire lines, has a characteristic impedance of 320 ohms which is sensibly constant over the whole operating waveband.

Further, the reduction in voltage for a given power indicates that the lines are free from corona effects even if the transmitters be operated under overload conditions.

The efficiency of the lines is also increased by the reduction of dielectric loss in the insulators.

It has now been decided to modify all feeders to the 4-wire type as soon as the present extensions to the station are complete.

in $\frac{1}{2}$ Z_0, and a further matching reactance M_3 is required. Thus the main feeders F_m are correctly terminated.

Since T_1 is equidistant from E_1 and E_2 and equal power is fed into each bay, the curtain is symmetrical and radiation will be normal to the line AB.

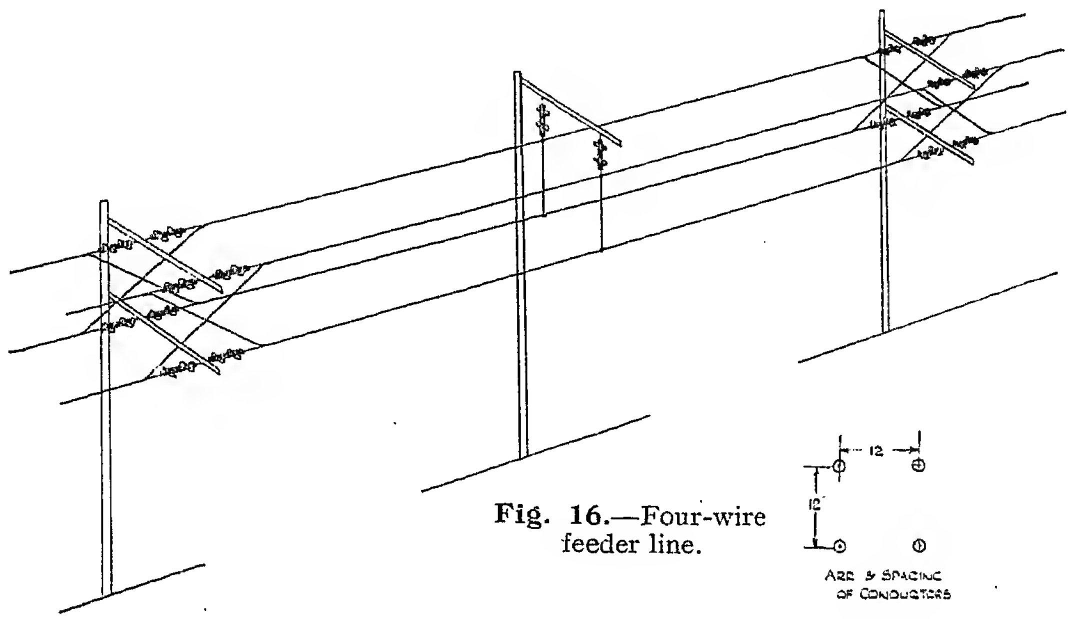


Fig. 16.—Four-wire feeder line.

(b) Single-Curtain Aerial Feeder

A diagrammatic elevation of an aerial and its feeders is shown in Fig. 17. The two similar halves or bays are fed separately by the feeders F_1 and F_2, vertical for approximately one wavelength; F_1 and F_2 then join the horizontal bay feeders T_1A and T_1B.

The nominal characteristic impedance Z_0 of all feeders is 550 ohms. In the Figure the current distribution is indicated by the dotted line and, since in general the bay

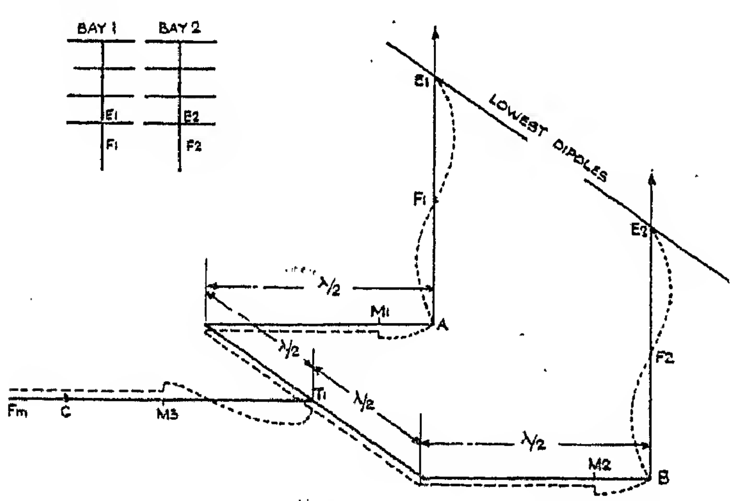


Fig. 17.—Aerial feeder system—single-curtain aerial.

impedances at E_1 and E_2 differ from Z_0, a standing wave exists on F_1 and F_2.

At the points M_1 and M_2 matching reactances are attached to the bay feeders; the values and positions of these are such that the apparent parallel reactance at the point of attachment is cancelled, and the parallel resistance remaining is equal to Z_0.

Between T_1 and M_1 or M_2 no standing wave is present and the currents in the two branches are equal and uniform. Thus the two bays are fed with equal power.

At the junction T_1 the feeder CT_1 will be terminated

(c) Reversible Aerial Feeder

The aerial just described normally radiates in both directions. It is often necessary, as previously explained, to confine the radiation to one of the two normal directions.

A reflecting curtain is added for this purpose and is similar in construction to the radiator, and switching is arranged so that either curtain can act as a radiator or reflector.

The feeder system for such an aerial is shown diagrammatically in Fig. 18. F_1 and F_2, F_3 and F_4, are the

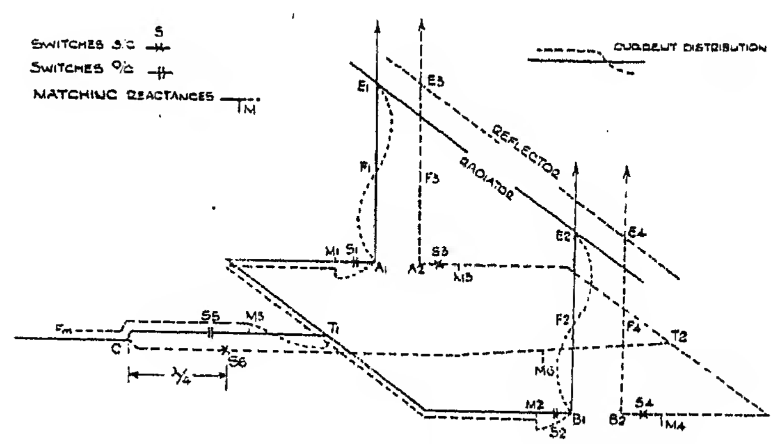


Fig 18.—Aerial feeder system—reflector aerial.

vertical bay feeders and are fed in pairs via the feeders T_1A_1, T_1B_1, and T_2A_2, T_2B_2.

The matching of each curtain to its feeder is exactly similar to the method already described.

One curtain only is fed at a time, the other acting as a parasitically excited reflector, and is isolated from the main feeders F_m by the switches S_5 or S_6.

Assuming that in Fig. 19 the full lines represent the radiating curtain, S_5 will be open and S_6 closed. S_6 thus short-circuits the feeder at a point $\frac{1}{4}$ λ from the junction C and thus, at this point C, the reflector feeders present

a high impedance whilst the radiator feeders present the impedance Z_0 and very little power is passed into the reflecting system.

Switches S_1 and S_2 are open, but S_3 and S_4 are closed. The latter switches are attached an odd number of quarter-wavelengths from the lowest elements of the reflector curtain. The idle feeders F_3 and F_4 thus present very high impedances at the points E_3 and E_4, and prevent power being fed into the feeder system from the reflector.

By these means the reflector curtain is effectively isolated from the feeder system, and the only currents flowing are those induced in the elements of the curtain.

To reverse the direction of radiation, switches S_3, S_4, and S_6 are opened and S_1, S_2, and S_5 closed, and, providing the matching has been carefully carried out, the main feeders F_m will be correctly terminated in both cases.

(d) Slewed Aerial Feeder

The radiation from a directional aerial may be slewed a limited amount by advancing the phase of the power fed into one bay ahead of that in the other bay. This is conveniently carried out in practice by making the lengths of the two bay feeders unequal.

Fig. 19 shows a single-curtain aerial which can be slewed on either side of the normal bearing. A reflecting curtain, also slewed, could be added, but for clarity is omitted from the diagram.

Assuming that radiation is desired along the bearing OT_2 (Fig. 19A), the curtain is to be fed by the feeders CT_2 and isolated from CT_1 and CT_3.

Switches S_2 and S_5 are open and S_1, S_4, S_3, S_6 all closed. As before, S_2, S_1, and S_3 are $\frac{1}{2}\lambda$ from the junction C, and when closed the feeders to which they are attached present a high impedance at C and therefore accept very little power.

Further isolation is necessary at T_1 and T_3, since the dead feeders would act as reactances in shunt across the line T_2B.

Thus S_4 and S_6, attached $\frac{1}{2}\lambda$ from T_1 and T_3 respectively, are closed, short-circuiting the lines and making their effective shunt reactive value negligible at T_1 and T_3.

The curtain is therefore fed with equal power by the feeders T_2A and T_2B, F_1 being advanced in phase by an amount $(T_2B - T_2A)$ wavelengths, causing the bearing of maximum radiation to be slewed off-normal and along a line OT_2 (Fig. 19A).

To change the bearing, the switches associated with the tapping point next required are opened and all others closed.

The matching points are M_1, M_2, M_3, M_4, M_5, and provide, as for the previous aerials, a correctly terminated load for the main feeders F_m, whatever the bearing of the aerial.

(e) Quarter-wave Switches

The switches S which short-circuit the feeders as required are, in practice, $\frac{1}{4}\lambda$ lines with means to open-circuit or short-circuit the lower end. Actually, therefore, when the switch is acting as a short-circuit to the feeders, it is open-circuited at its lower end. The use of such $\frac{1}{4}\lambda$ lines enables the manually operated portion of the switch to be arranged at a convenient height above ground, and also the effect of supporting insulators can be removed by suitably adjusting the actual length of line in circuit.

(f) Matching Reactances

The matching reactances employed are those first described by Sterba and Feldman* and consist of lengths of feeder whose constants are similar to those of the main feeders.

As is well known, such short lines act as inductive or capacitive reactances, depending on their length and whether they are open-circuited or short-circuited at the free end.

A complete range of reactance values is thus possible. In practice short-circuited lines are used, if necessary more than $\frac{1}{4}\lambda$ long, since the lower end can be earthed and no high-voltage point is brought near to the ground.

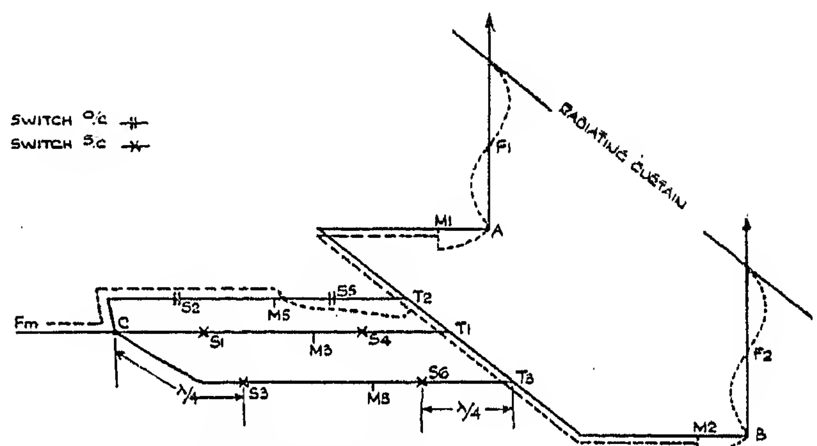


Fig. 19.—Aerial feeder system—slewed aerial.

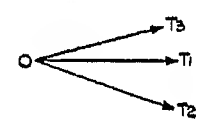


Fig. 19A.—Bearings of maximum radiation.

(g) Switching Frame

The decision to use feeders of the open-wire type simplified considerably the design of the switching system. It has been mentioned that the Empire scheme as originally planned involved the use of 22 aerials and 6 transmitters. It was obviously impossible to design any switching system which would permit the connection of any transmitter to any aerial, especially in view of the fact that extension was contemplated to the number of aerials and transmitters envisaged in the original scheme.

To assist consideration of the problem, the operating department prepared representative schedules showing various convenient combinations of aerials and transmitters. These schedules covered not only the daily switching operations but also those involved by the seasonal variations in propagation conditions referred to in an earlier Section of this paper.

Examination of the schedule showed that, for long periods, an individual transmitter could be associated with groups of 4 to 6 aerials but that the seasonal changes would involve considerable modification to this

* *Proceedings of the Institute of Radio Engineers*, 1932, vol. 20, p. 1163.

grouping. The switching system therefore resolved itself into two definite parts: (*a*) daily switching, and (*b*) seasonal switching.

It was apparent that any system of switching would involve using a large number of switches, and that these switches and associated feeders should be amply spaced to avoid interaction of any type. The design of an open-air switching station was therefore indicated.

It is not necessary to emphasize the fact that a switch for connection in series with high-frequency feeder lines must simulate the electrical characteristics of the feeder. Large masses of metal, either in the conducting part of the switch or in nearby supporting and operating structures, cause variations in impedance which cannot be tolerated.

There is no normal type of switch which would fulfil these requirements and it was decided that the selector switches should take the form of manually operated links, the link consisting of a length of feeder line. The design adopted is depicted in plan and elevation in Fig. 21.

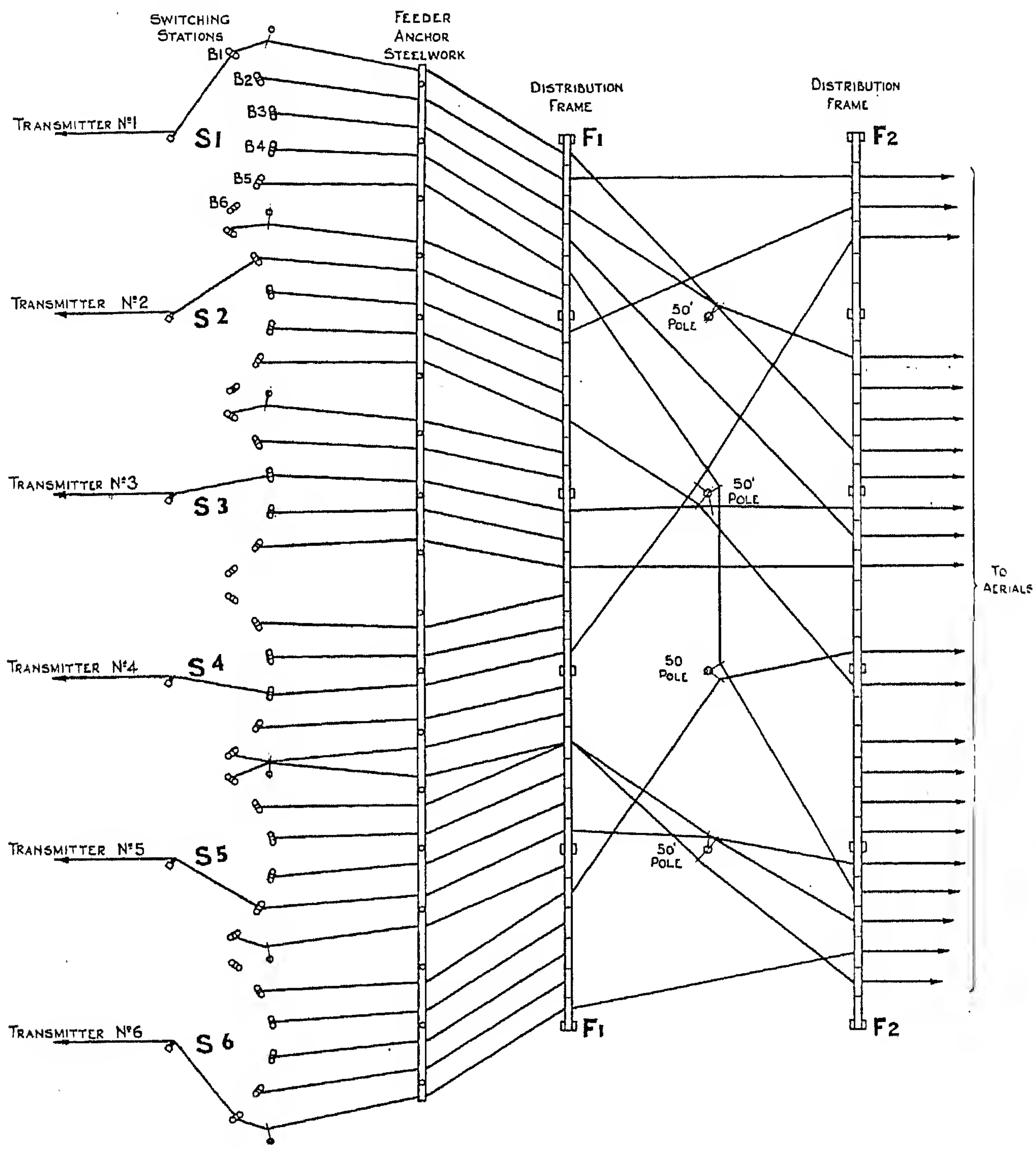


Fig. 20.—Schematic of feeder switching system.

Many schemes were considered, and the one finally adopted is shown in diagrammatic form in Fig. 20.

The arrangement consists of a number of double-pole selector switches S_1 to S_6 and an intermediate distribution frame F_1, F_2, the transmitters being connected to the moving arm of the switches and the outgoing feeders to the fixed contacts, the latter passing through the distribution frame on the way to the aerials.

Daily switching operations are carried out on the switches, seasonal redistribution being effected by jumper wires in the distribution frame.

The feeder from the transmitter is secured to two insulators on top of Pylon A. These insulators are placed one above the other in order to bring the lines into vertical formation to permit the swinging link to move on a radius. This is achieved by turning the feeder through 90° in the distance from the last supporting pole to Pylon A. From the insulators two conductors of

195/·010 parallel-lay dynamo flex are connected by bronze shackles. The other end of the conductors is terminated in two hooks which are separately mounted on pillar insulators supported on the end of an ash rod.

The hooks engage in the D-shaped eye contacts which are mounted on insulators on the top of the pylons B1/6. The inner surface of these D-shaped contacts is serrated. The conductors are arranged to have a considerable degree of slack, which is taken up after the hook is engaged by the straining wire connected to winch C, a tension of about 15 lb. being applied. This

On a line midway between the two frames are placed four 50-ft. poles. The steelwork of each frame is designed to divide each into 30 bays, each bay being provided with a twin set of rod-type insulators mounted between L section steel brackets. The vertical members of the frame are drilled so that the brackets can be bolted to them at heights of 10, 16, 22, and 28 ft.

Plate 4 shows the frame, with the selector switches in the foreground.

The frame is of lattice-steel construction and of sufficient strength to take the unbalanced pull of all the

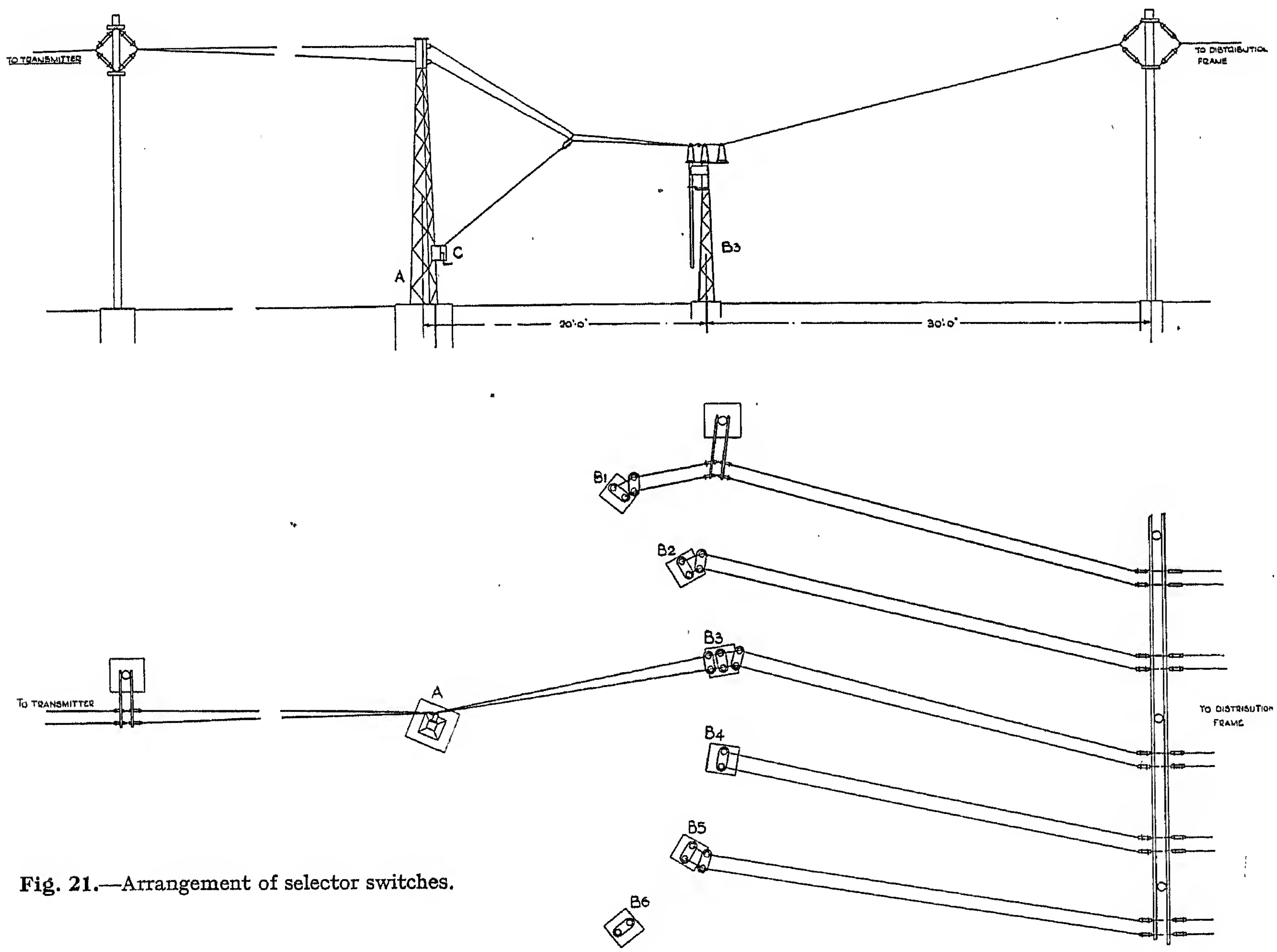


Fig. 21.—Arrangement of selector switches.

tension is sufficient to make the serrations on the inner surface of the D contacts bite into the hook.

The constructional details of the hook switch are shown clearly in Plate 3. This type of switch is simple and cheap to construct, and, in spite of the fact that the feeder current of 15 amp. is carried through a bronze shackle at one end and a hook at the other, not a single case of bad contact has been reported.

It is interesting to note that practically no heating occurs at these contacts.

From the fixed contacts of the selector links the feeders pass through a supporting frame to the transmitter side of the main distribution frame. This consists of two frames each 190 ft. long and 30 ft. high, disposed parallel to each other at a distance of 60 ft.

feeders on one side. The proportions of the frame were so chosen that feeders running on nearly parallel routes would have a clearance between them of about 6 ft., but some reduction in this spacing was necessary in the case of feeders which crossed at angles approaching 90°. This applies to the jumper wires, which run diagonally from frame to frame and are supported on the 50-ft. poles. These poles are fitted with brackets which carry insulators, arrangements being provided to enable the brackets to swivel in any desired direction.

(6) BUILDINGS

The building is constructed to accommodate four transmitters, together with a substation and an emergency Diesel generating station. It is divided into two

sections placed at a short distance from each other, the main building containing the transmitters and the power plant directly associated with them, offices, stores, etc., while the second building accommodates the substation, consisting of high-voltage and low-voltage switch-rooms and two 750-h.p. Diesel generating sets. Two 2 500-kVA transformers are placed outside the substation building.

The transmitter portion of the building was designed in such a manner that an extension could be built at the rear and, at the time of writing this paper, this extension is under construction.

The layout of the building and the associated plant is shown in Fig. 22. This plan is to a large extent self-explanatory and it is unnecessary to describe the layout of the plant shown. The plan does not, however, show the basement, which is formed beneath the transmitter halls in both buildings. This basement accommodates the main cooling-water storage vessels, cooling-water circulating pumps, smoothing condensers, and other auxiliaries associated with the transmitters.

The building is a steel-and-brick structure with facings of Empire stone. Its position on the site can be seen by reference to Fig. 14.

All circuits of the transmitters were specified to be arranged for rapid adjustment to four predetermined wavelength bands.

It was further specified that the radiated frequencies should be stabilized to within $\pm$ 1 part in 100 000 by crystal oscillators, 11 crystals to be provided, each ground to one of the operating wavelengths allocated to the service.

Four sets of harmonic generators were called for, which would be pre-set to one of the four wavelengths allocated to a particular transmitter.

An auxiliary valve oscillator was also specified which was capable of continuous adjustment over the whole waveband. This oscillator was required as a spare for the crystals and for the purpose of covering frequencies intermediate to those provided by the crystal oscillators. The frequency stability of this oscillator was specified as within $\pm$ 1 part in 25 000.

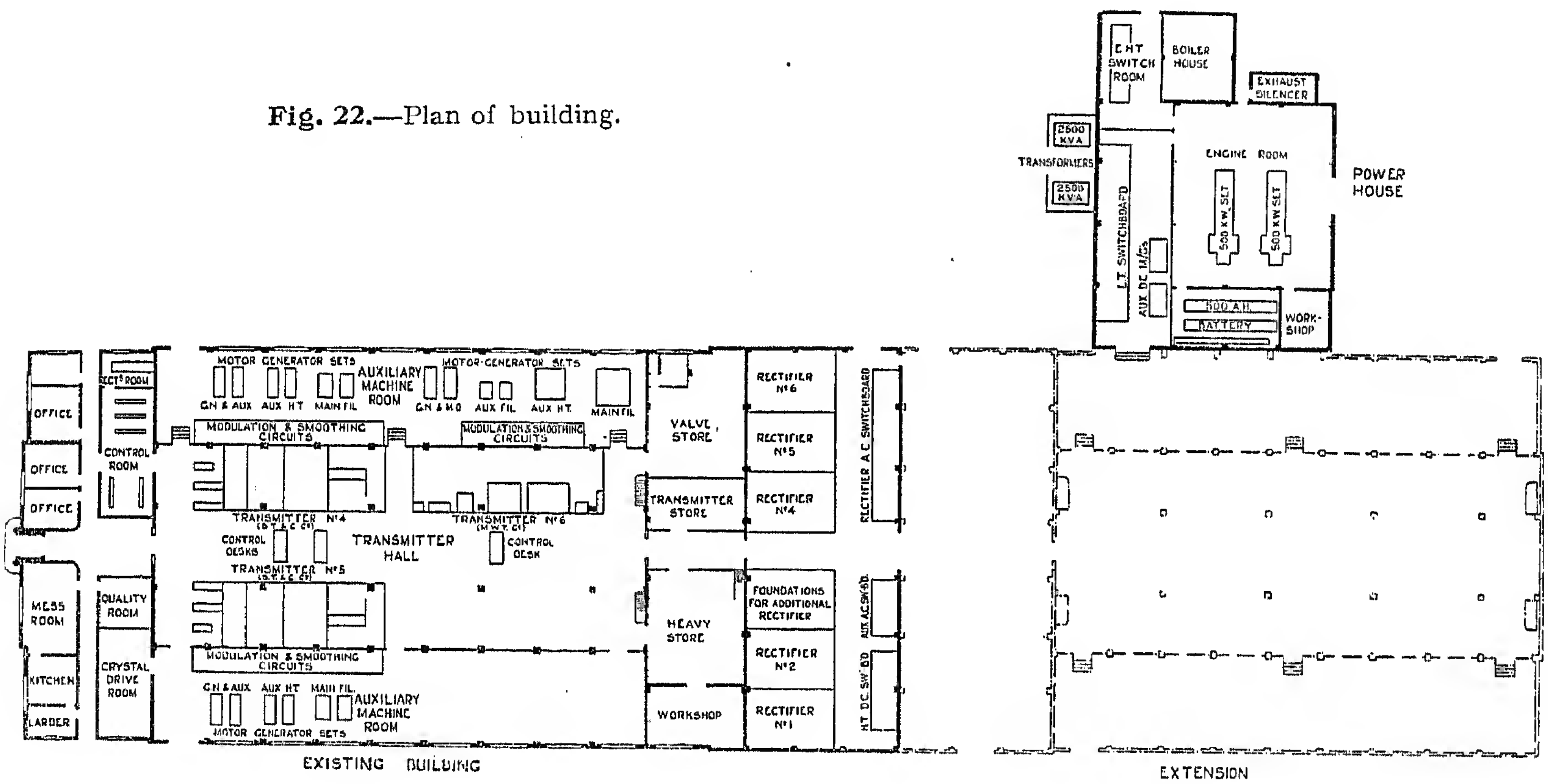


Fig. 22.—Plan of building.

(7) TRANSMITTER PLANT

(a) General

The transmitters were specified to cover a wave-range of 13·5 to 80 m. and to have an unmodulated carrier output of 80 to 100 kW. Rapid wave-change facilities were desired and, in view of the difficulties of adjusting short-wave transmitters, the specification required that the number of adjustments to obtain a given wavelength were to be reduced to a minimum. Designs which involved individual change of inductance, capacitance, or resistance values were not considered. Further, it was specified that critical adjustments to circuits after wave-change must be avoided.

The output circuits of the transmitter were to be designed to match the impedance of an open-wire balanced feeder, having an impedance of approximately 550 ohms.

Whether or not spare valves were to be provided in the high-power stages was left to the discretion of the designers, since the difficulty of providing switching facilities for high-power valves on the shorter wavelengths was appreciated.

The system of modulation was not definitely specified, but it was indicated that preference would be given to designs in which modulation was effected at the anodes of the final high-frequency stage. This was considered desirable in order to avoid the necessity for precise adjustments which are necessary on modulated power amplifier stages.

It was specified that the r.m.s. sum of the harmonic content on any frequency of modulation should not exceed 4 % of the voltage of the fundamental modulation frequency at a modulation depth of 90 %. The

overall frequency response was specified to be constant from 50 to 8 000 c./sec. with a tolerance of $\pm$ 2 db.

(b) Marconi's Wireless Telegraph Co., Ltd., Transmitter

The transmitter supplied by Marconi's Wireless Telegraph Co., Ltd., is designed for a maximum unmodulated output to the feeder of 100 kW at wavelengths between 30 and 80 m., and 75 kW at 13·5 m., rising to 100 kW at 30 m.

Series modulation is employed, the modulators being connected in series with the main high-frequency amplifier. Wave-change is effected by means of circuits mounted in trucks, one truck being provided for each of the four wave channels on which it is desired to operate the transmitter. This system is applied to the three final high-frequency amplifiers. The circuits of the low-power amplifiers and harmonic generators are pre-set, a separate set of equipment being provided for each of the four working wavelengths.

It will be appreciated that the number of wavelengths on which the transmitter may be operated may readily be increased by increasing the number of circuit trucks.

A diagram of the circuits of this transmitter is shown in Fig. 23. It will be observed that the series modulators are at high potential, which necessitates insulating the filaments of these valves and making special provision for feeding the low-frequency input to the grids. A circuit of unusual design was developed for this purpose and will be described later.

The high-frequency circuits, while of conventional type, are of interest in design and layout. It will be appreciated that the designers of this transmitter were confronted with a difficult problem in producing a transmitter using valves as large as the CAT.14SW in a final amplifier which would operate and be stable and easy to handle at wavelengths as low as 13·5 m. and simultaneously provide the rapid wave-change facilities called for.

The whole of the circuits of the main amplifier are contained in a cubicle measuring 8 ft. 6 in. × 8 ft. × 7 ft. high. The framework of this cubicle is constructed with brass angle members and panels of perforated brass sheet. The two CAT.14SW valves are mounted towards the front of this cubicle, the base of their water jackets being mounted on two machined bronze surface-plates, which are insulated from the floor by a plinth formed with slabs of mycalex (see Plate 5, which shows one of the CAT.14 valves and its associated components).

To the inner edge of the mounting plates are bolted massive cast aluminium U-shaped plates which form one electrode of the balancing and anode-circuit tuning condensers. The manner in which these condensers are constructed is shown clearly in Plate 5. The U-shaped electrode marked "a," together with electrode "b," form the anode tuning capacitance. Electrode "b" is isolated from earth so far as the operating frequency is concerned, and forms a capacitance from anode to anode. It is, however, earthed through a resistance which provides a measure of stabilization to spurious parallel

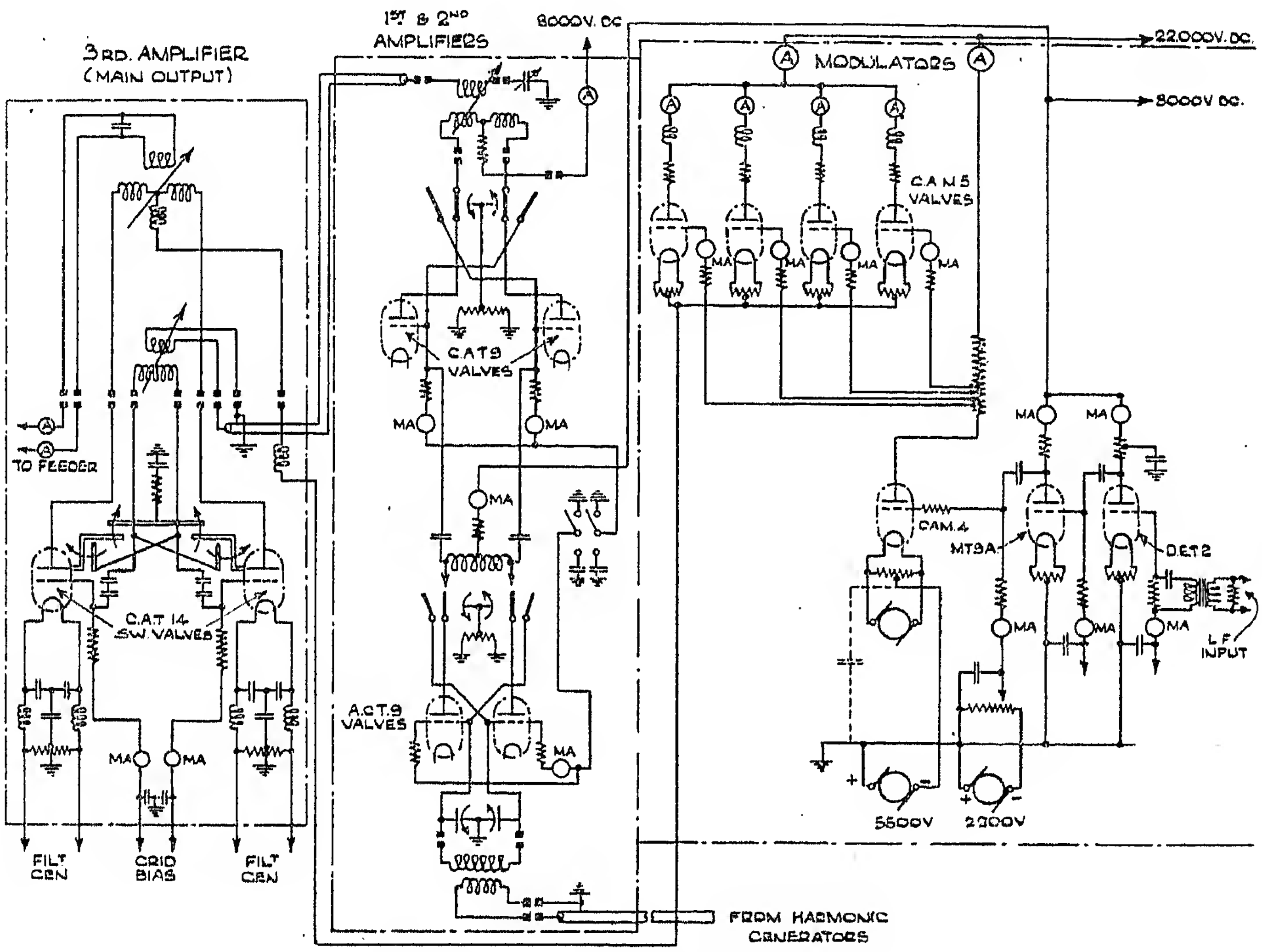


Fig. 23.—Circuit diagram of power stages of Marconi transmitter.

oscillations. The spacing between "a" and "b" is variable, "b" being moved by a hydraulic ram which is controlled by a handwheel on the front of the transmitter.

Neutralizing capacitance is formed by electrodes "a" and "c," electrode "c" being formed by two oblong-shaped plates which are pivoted on the column "d." Variation of capacitance is obtained by folding the plates together in the direction which takes them away from "a." This movement is produced by the operation of a second hydraulic ram.

Attention is directed to the vertical busbar, the top portion of which is shown. This is one of two similar busbars mounted on the circuit trucks from which the anode inductances are supported.

A typical circuit truck is shown in Plate 6. The anode and grid inductances associated with the CAT.14 valves are mounted on these trucks, which are inserted from the rear of the cubicle. The circuits of the truck depicted are set up for a wavelength of 49 m. By way of contrast Plate 7 depicts a second truck, the circuits of which are set up for 16 m.

The mechanical construction of these circuits can clearly be seen. The anode inductance is bolted to the two vertical busbars referred to above. At the opposite side, to which the turns are bolted, are fixed two vertical knife-edges which are constructed with thin copper sheet wrapped on a flexible core. When the truck is pushed into position these slide between two copper jaws, which are closed together with a vice-like action when the pedal shown in Plate 7 is depressed. A vice-type contact is also used on the top plate of the CAT.14 anode water jacket.

A railway track with sidings is provided on which the trucks are run. A truck entering the cubicle, and other trucks in the sidings, are depicted in Plate 7.

The design permits of considerable latitude in the set-up of the anode circuits, and this is demonstrated by comparing the two trucks illustrated. In the case of the 16-m. circuit, the inductances are built up with 3 in. diameter copper tube. The portion of the rectangular turn projecting from the uprights is arranged to telescope, which provides a fairly fine adjustment of inductance when the circuit is being set up. The feeder coupling coil is arranged to slide between the centre turns of the anode inductance, in which position capacitance effect between the coils is at a minimum. This coupling coil is supported from the structure of the feeder condenser, and the whole assembly is mounted on guides which allow the position of the coupling coil to be moved relative to the anode coil, the movement being effected by means of a hydraulic ram.

The feeder-coupling circuit condenser is pre-set and is not provided with an external control, although such an adjustment would prove to have some advantage in permitting a greater range of compensation for feeder impedance variations than is provided by the variable coupling.

The grid-circuit inductance is mounted at the top of the truck on four curved mycalex supports. This coil is designed on the same general lines as the main anode coil, but of course is of much lighter construction. The grid tuning condenser is permanently mounted in a screening box inside the transmitter, into which the coil also slides, contact being made by means of the copper bars which can be seen in Plates 6 and 7.

The hydraulic rams which are used to control the anode tuning, feeder coupling, and balancing condenser adjustments, are actuated by a Lockheed master cylinder operated by means of a handwheel mounted on the front of the transmitter. One handwheel and one master cylinder only is provided, the ram to be used being selected by means of three cocks mounted above the handwheel. Three vernier scales, mounted above the handwheel, show the position of any of the three adjustments.

This type of control is smooth and free from backlash. It is thought that this is the first occasion on which hydraulic control has been used for the purpose of controlling variables in a wireless transmitter. The system has many advantages, as it avoids subverting the layout of the high-frequency circuits to the layout of controls, which is sometimes the case where direct mechanical control is used.

It will be observed from the diagram of connections that the reactance of the filament leads of the CAT.14SW valves is neutralized by a condenser. This condenser is mounted in a screened box situated at the top of the cubicle immediately above the valve filament connections. The filament-heating current is led through stopper inductances, which are also mounted in a screened box.

All wiring, other than that associated with the main high-frequency circuits, is led to its terminal points within the cubicle in copper trunks and is therefore completely screened from the influence of high-frequency fields which may exist within the unit.

The first and second amplifiers are designed on similar principles to the main amplifier, although the circuits are of course lighter in construction. Space does not permit a full description of this portion of the equipment, but the detailed description of the main amplifier gives a clear indication of the principle of design.

These two amplifiers are mounted one above the other in a cubicle, and their circuits are mounted in a single truck. The second amplifier, which is mounted in the base of the cubicle, consists of two CAT.9 water-cooled valves, while the first amplifier consists of two ACT.9 radiation-cooled valves. The grids of these valves are excited from the low-power amplifier, which consists of six DET.5 valves in parallel push-pull which form the final unit of a 6-stage harmonic amplifier.

These amplifiers are rack-mounted. Five sets of amplifiers are provided, four of which are set up to the four frequencies allocated to the transmitter, while the fifth is associated with a variable-frequency oscillator which acts as a spare for the other four equipments.

The four harmonic amplifiers which are set up for definite frequencies are coupled by means of concentric feeders to the crystal oscillator. This is duplicated, and each set consists of 11 crystals mounted in a temperature-controlled chamber. The crystals are mounted on a turret within the oven which can be rotated by means of a handle at the top of the oven.

The modulation circuits are shown in Fig. 24. The main modulators consist of four CAM.5 valves connected in parallel. As mentioned previously, these

valves are placed at the high-potential end of the circuit, while the high-frequency valves are at the low-potential end. This arrangement was adopted owing to the difficulties which would have been encountered had the high-frequency valves and associated circuits been placed at high potential.

While the arrangement simplified the design of the high-frequency circuits, it introduced difficulties in feeding the low-frequency input and grid bias to the grids of the main modulators. A special circuit was, however, designed to overcome this difficulty. The arrangement consisted of a resistance in series with the anode of a CAM.4 valve, the filament of the valve being connected to earth through a generator producing a negative voltage of 5 500.

A simplified version of the circuit is shown in Fig. 24. It will be observed that this is in reality a potentiometer circuit, the grids of the CAM.5 valves being tapped on to the CAM.4 anode resistance in such a manner that they assume the correct potential relative to the filament and anode. This circuit permits the correct grid bias to be applied to each valve, and the applied grid excursion to be automatically adjusted to suit the bias applied.

The grid of the CAM.4 valve is connected to a 2-stage resistance-capacitance-coupled amplifier consisting of one MT.94 and one DET.2 valve, the anode voltage of these valves being supplied from a separate source. It will be noted that the CAM.5 valves and the high-frequency load form a cathode follower system for which the following advantages are claimed by the designers:—

(1) Non-linearity of the characteristics of the CAM.5 valves has only a secondary effect on the linearity of the output, provided the grid swing is linear.

(2) The hum level due to the a.c. heating of these valves is very small, since no voltage magnification occurs in the CAM.5's.

(3) With a non-linear load the voltage-swings across the load are still almost linear.

(4) If the load resistance be varied over wide limits the voltage across the load varies only slightly, and the modulator settings are still satisfactory. Such a variation in load resistance occurs in practice when the output coupling of the high-frequency amplifier is adjusted.

(5) If one modulator burns out or is removed, the remaining three take up the load automatically.

(6) Variation in the anode d.c. supply produces a much smaller variation in the voltage across the load, which indicates that if a ripple be present in the applied H.T. voltage, then its effect on the high-frequency amplifier is much reduced.

(7) When the valves have been adjusted to take equal d.c. anode current, then the a.c. load will also be automatically adjusted to suit the characteristics of the individual valves.

The general layout of this transmitter is shown in Fig. 25. This plan is self-explanatory.

The power supply for the modulators and main amplifier is derived from mercury-arc rectifiers having a d.c. output at 22 000 volts. The filaments of the modulators are lighted by a.c. transformers in Scott connection.

The filaments of the two CAT.14 valves in the main

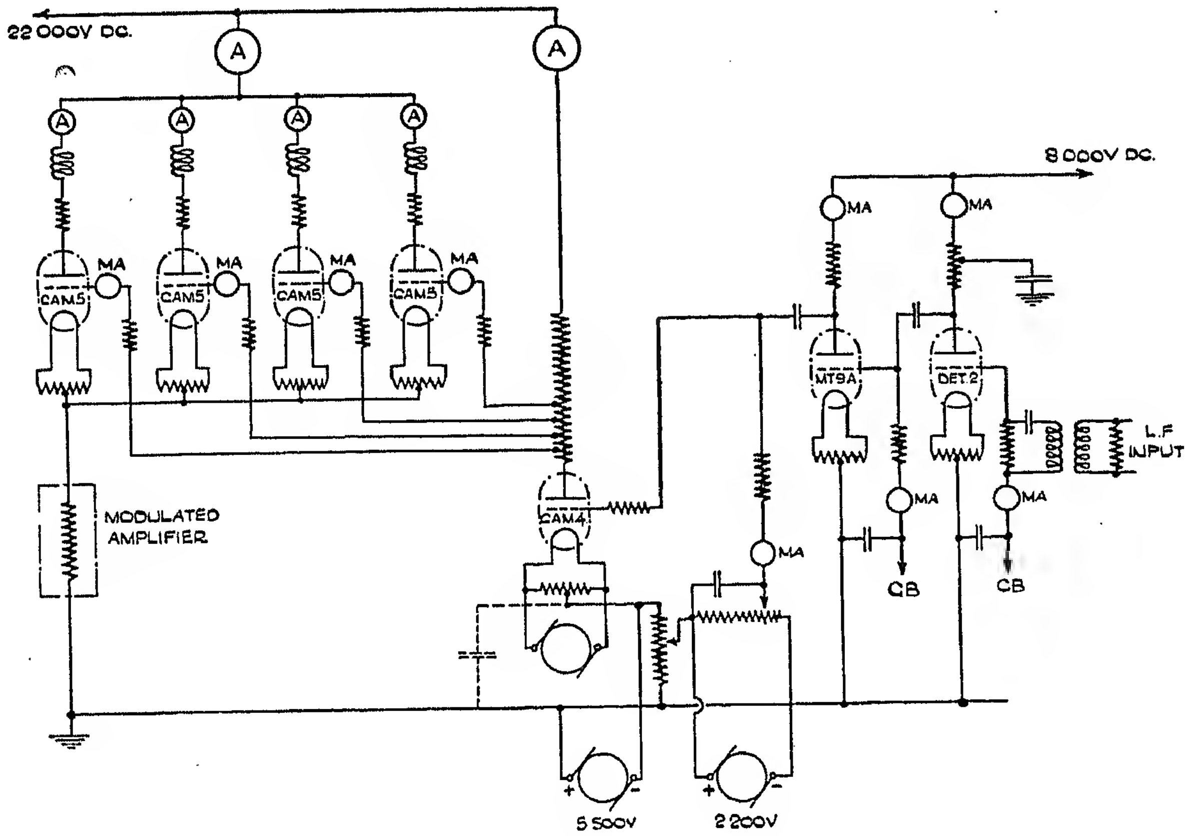


Fig. 24.—Simplified modulation circuit diagram of Marconi transmitter.

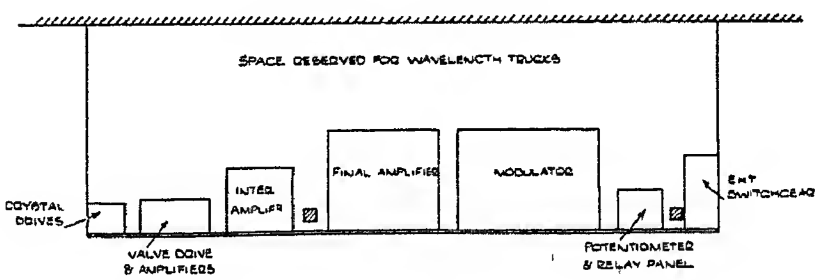


Fig. 25.—Layout of Marconi transmitter.

amplifier are each independently heated by a d.c. generator, the control of filament voltage being carried out by means of the field regulator.

The whole transmitter is enclosed by a straight-fronted framework consisting of aluminium and steel panels except in the vicinity of the high-frequency amplifiers, where copper or brass is used.

The smoothing condensers, insulating hose coils for the modulator, and certain other auxiliaries, are mounted in an enclosure situated in the basement immediately beneath the transmitter. The doors of this enclosure are interlocked, as are the doors of the main transmitter enclosure. This interlock system makes it impossible for the doors to be opened unless power is first switched off, and the power cannot be switched on while any door is open.

The interlock system is electrically and mechanically constructed so that two systems must fail before a condition which may be dangerous to operating personnel can be produced.

The following results were obtained during tests on this transmitter:—

Performance on 25·30 m.

Output power (unmodulated)	98 kW
Efficiency of modulated amplifiers (including valve conversion and output circuit losses)	64 %
Total power consumption from mains, including all auxiliaries, 100 kW output (constant with modulation)	545 kW
Overall efficiency on carrier	18·3 %
Overall efficiency on 100 % modulation ..	27·6 %

Harmonic Distortion

Tone frequency	Harmonic content at 90% mod.	70% mod.	50% mod.
40	3·6	2·1	1·7
400	4·8	3·2	0·7
4 000	3·8	2·4	0·8
8 000	3·3	2·3	0·8

Frequency Response

− 1·3 db. at	50 c./sec.
0 db. at	1 000 c./sec.
− 0·7 db. at	8 000 c./sec.
− 0·9 db. at	9 500 c./sec.

Noise Level

The r.m.s. value of the noise was found to be 54 db. below 100 % modulation.

(c) Standard Telephones & Cables, Ltd., Transmitters

The two transmitters supplied by Standard Telephones & Cables, Ltd., were designed for a maximum unmodulated output to the feeder of 80 kW at wavelengths between 30 and 80 m. and 52 kW at 13·5 m., rising to 80 kW at 30 m.

A Class B modulator system is employed on these transmitters, modulation being effected at the anodes of the main high-frequency amplifier.

Wave-change is effected by means of circuits mounted on turntables. This system is applied to the penultimate and main high-frequency amplifiers. The circuits of the low-power amplifiers and harmonic generators are pre-set, a separate set of equipment being provided for each of the 4 working wavelengths.

The use of turntables for effecting circuit change permitted the use of spare valves, which is an achievement in transmitters of this power and wavelength.

The high-frequency circuits of the penultimate and final amplifier are shown in Fig. 26. It will be noted that the system of coupling between the penultimate and main amplifiers is of unusual interest, since the grids of the main amplifier are earthed and the filaments insulated, the exciting circuit being connected between them. Amplifiers of this type are usually referred to as "series connected" or "inverted."

This system was chosen because it possesses the following advantages:—

(1) Provides inherent reverse feed-back, stability being obtained without the use of balancing condensers or with balancing condensers of extremely low capacitance.

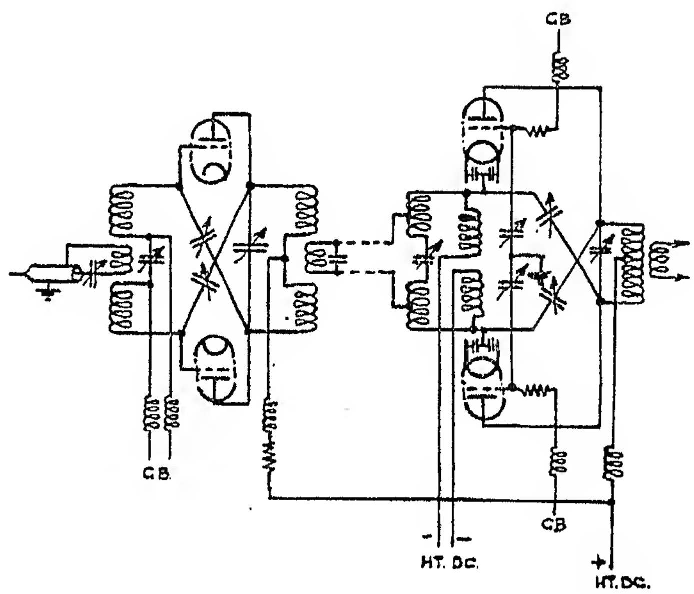


Fig. 26.—Series-connected amplifier of Standard transmitter.

(2) The elimination of balancing condensers reduces the capacitance across the anode tank circuit by one-half as compared with an amplifier of conventional design using a similar type of valve.

(3) The overall efficiency of the transmitter is increased because a large proportion of the power output of the exciter amplifier is fed into the aerial.

The penultimate amplifier in this particular case consists of two SS1971 valves connected to a push-pull balanced circuit, the anode tank circuit being inductively coupled to the insulated filaments of the main amplifier, which consists of two 4030 B. valves. The grids of this amplifier are connected together and earthed, the reactance of the connecting lead being neutralized by series condensers. The anodes are tuned by an L,C circuit of conventional design which is magnetically coupled to the feeder.

Attention is drawn to the following important points in the operation of this type of circuit:—

(i) The earthed grids form a screen between anode and filament, and, provided the grids are connected together and earthed through a path which does not possess impedance, there can be no direct transfer of

radio-frequency energy between anode and excitation circuits.

(ii) The anode-grid capacitance of the valves forms a portion of the output tank circuit capacitance. A portion of the circulating current in this circuit therefore flows between the anode and grid capacitance and through the connecting lead between the grids.

(iii) The anode and grid circuits are coupled only through the medium of the anode space-current, and this current traverses the grid-filament exciting circuit.

The significance of these points is best demonstrated by reference to Fig. 27, in which a series amplifier is shown in its simplest form.

The grid exciting circuit is represented by the alternator A, and the driving e.m.f. produced by the action of the valve in conjunction with the applied d.c. potential by the alternator B.

The polarity of the various parts of the circuit and the direction of currents at the instant when the valve is conductive are marked on this Figure.

It is clear that the anode current which traverses the grid circuit is in such a direction as to load this circuit, since the instantaneous polarities of alternators A and B are in such a sense that they add.

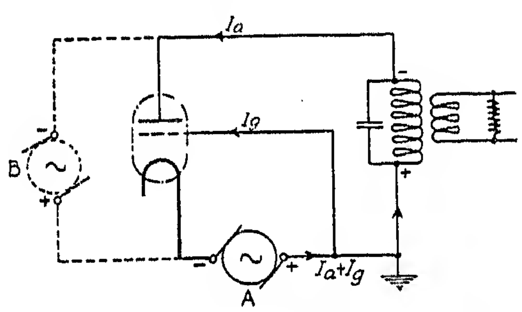


Fig. 27.—Equivalent circuit of series amplifier.

It is clear, therefore, that the e.m.f. applied to the load circuit is the sum of the e.m.f.'s of these two alternators.

Consideration shows that such a condition is equivalent to a negative feed-back and produces a circuit which is inherently stable on its fundamental wavelength. In an amplifier of this type the power output of the exciter is determined not only by the power required to drive the valve but by the anode current at which the valve is to be operated.

If I_a represents the anode current for a given operating condition, E_g the r.m.s. voltage required to excite the grids, P_g the power required to drive the grids, the power output of the exciter stage is therefore $(E_g \times I_a) + P_g$.

A variation in anode circuit impedance or applied d.c. voltage will cause a variation in anode current which will also modify the load on the grid circuit. Modulation cannot be effected by variation of anode voltage unless the exciter amplifier has perfect regulation (which is of course impossible) or is also anode-modulated.

It is the practice, therefore, to apply modulation to the anodes of both the final and exciting amplifiers. If both amplifiers be designed to operate at a similar anode d.c. potential, then modulation may be effected from one set of modulators. This is the arrangement adopted in these transmitters.

An advantage of this system is its high overall efficiency due to the utilization of the power delivered to the penultimate stage.

Since the grids of the main amplifier are maintained at zero potential with respect to earth, and the exciting potential is applied to the filaments, it is therefore necessary to feed the filament-heating current through stopper circuits or by means of low-capacitance transformers, which presupposes the use of alternating current. In the case of these transmitters the filaments are heated by direct current fed through stopper circuits.

The grids of the penultimate amplifier are excited by two Type 4278A valves which are of the tetrode type. These valves are connected in parallel and have a total output of 1 kW approximately. They are in turn excited from the output of one of four pre-set harmonic generators.

The circuits of the 4278A amplifier and the harmonic generators are of conventional design, and it is not proposed to give a detailed description.

Circuit Details of the Modulation System.

The modulator circuits of this transmitter are shown in Fig. 28.

The main modulators consist of two 4030B valves connected in push-pull, operating as Class B amplifiers.

The modulated amplifiers and the modulators are transformer-coupled and it will be observed that the secondary of the transformer is coupled to the modulated amplifier by an inductance-capacitance arrangement. This scheme has of course been adopted to avoid passing the d.c. feed to this stage through the secondary of the transformer. On the primary side, the d.c. feeds to the modulators balance out.

The grids of the modulators are transformer-coupled to two 4058A valves, which are in turn inductance-capacitance-coupled to two 4270A valves.

It will be observed that a system of negative feed-back is used, having the effect of reducing the total harmonic content to a very low value.

The Figures referred to also show the smoothing and the decoupling circuits used in the H.T. feed. These circuits are of normal design and do not require special comment.

The principle of the Class B modulator system equipped with feed-back is now well known, and the high conversion efficiency and low harmonic content claimed for this system have been fully borne out by the results obtained from the two transmitters under discussion.

Overall efficiency and distortion figures are given at the end of this Section.

Construction of the Transmitters.

Structurally these transmitters are divided into two sections, the first consisting of rack-type equipment on which is mounted the crystals, maintaining circuits, harmonic generators, and output amplifiers, also the l.f. amplifiers; the second section consists of the penultimate and main h.f. amplifiers and the penultimate and main modulator stages. These stages are enclosed in a straight-fronted enclosure 7 ft. high and 42 ft. long.

This enclosure is partitioned internally into 5 compartments. The first compartment contains the H.T.

safety switch, which is interlocked with the doors of the enclosure. The second and third enclosures contain the penultimate and main h.f. amplifiers. In the fourth and fifth are mounted the water-cooled modulator stages.

Fig. 29 shows a simplified plan view of the layout of these amplifiers. It will be observed that the turntables carrying the circuits, each of which is set up for one of the four spot waves on which the transmitter is adjusted to work, are mounted between the two pairs of valves, one of which is designed to be the working set and the other set spare.

Connection between the valves and the circuits is effected by means of motor-operated switches, which are clearly illustrated in Plate 8. In this Plate the important components are also clearly indicated. The turntable is driven by means of a motor situated in the basement, and control circuits are provided by means of which the turntable can be operated from the front of the transmitter.

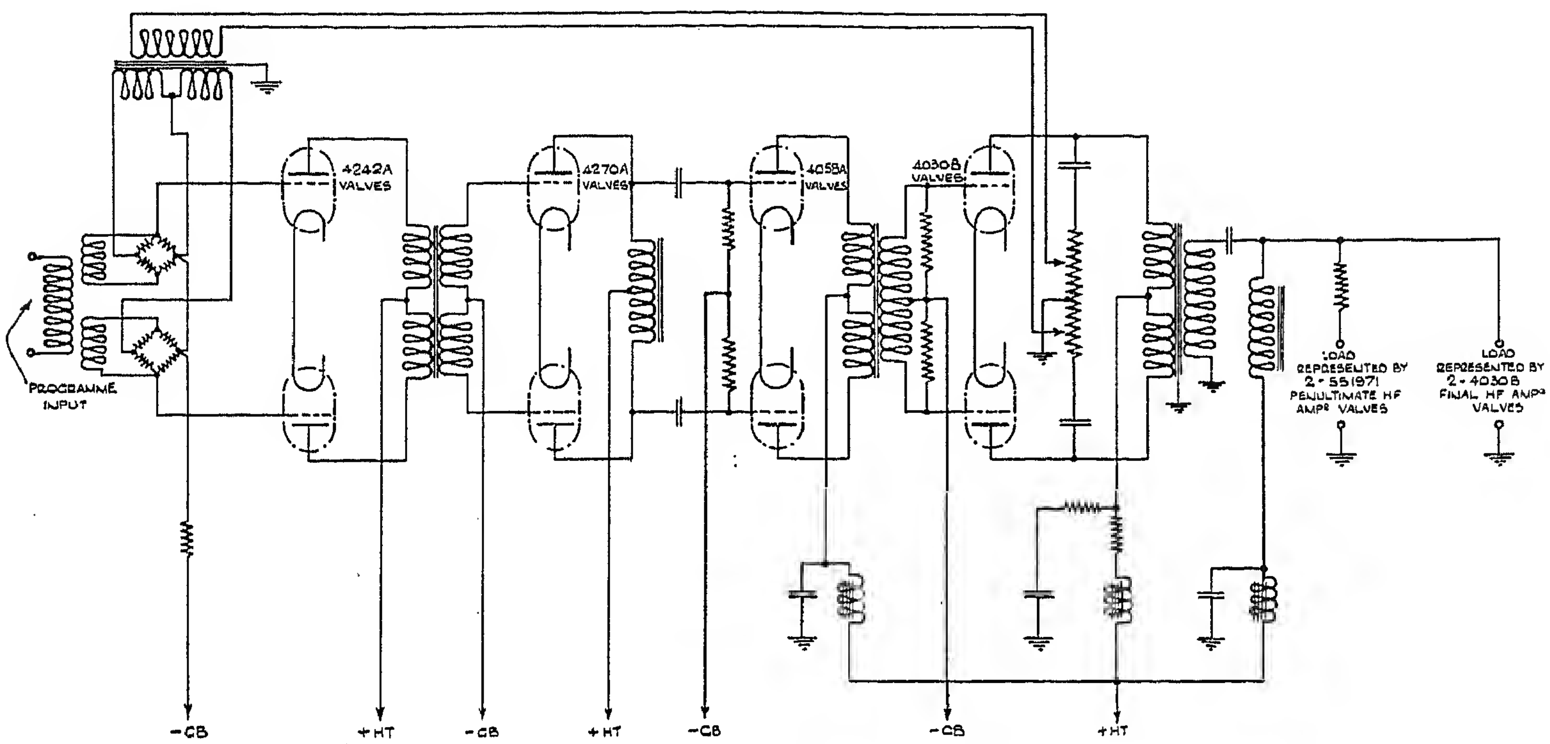


Fig. 28.—Modulator circuits of Standard transmitter.

The valves are mounted on steatite pedestals which are hollow, the cooling water being led through the centre of these pedestals through the floor to porcelain insulating hose coils which are situated in an interlocked enclosure in the basement immediately beneath the transmitter.

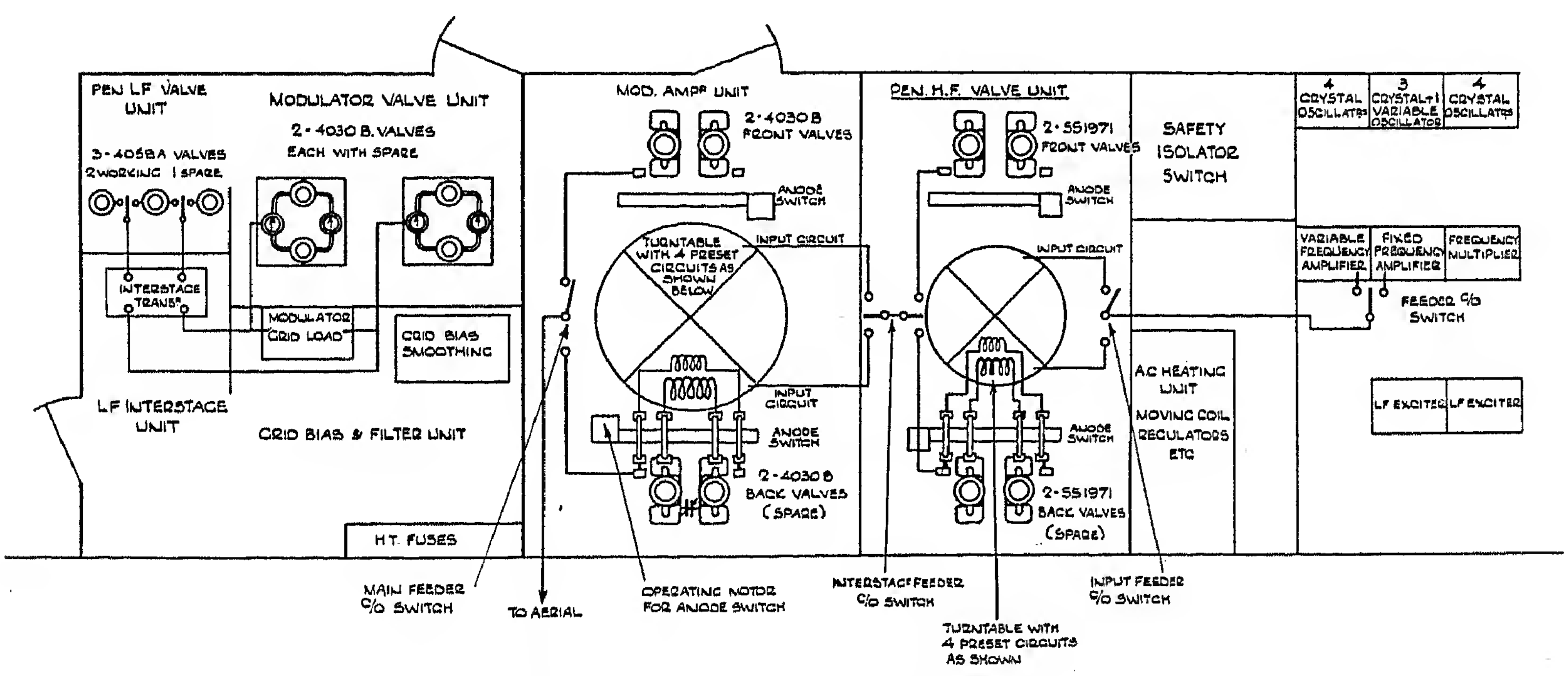


Fig. 29.—Layout of Standard transmitter.

The turntable is constructed of Duralumin and the circuits are contained on two shelves, on the upper of which are mounted the anode tank circuit inductances and the feeder coupling coil. On the lower shelf are mounted the input circuit and the necessary coupling coils.

Rather elaborate arrangements are provided for controlling the water flow to the working and spare valves,

which are interlocked with the turntable operating mechanism.

The transmitter enclosure is provided with three doors, which are interlocked with all transmitter supplies.

The following results were obtained during tests on the above transmitters:—

Performance on $31 \cdot 5$ *m.*

Output power (unmodulated) = 80 kW
Efficiency of two last radio-frequency stages = 64 %

Total power consumption from mains (80 kW carrier), including all auxiliaries:—

0 % mod.	240 kW
30 % mod.	258 kW
100 % mod.	321 kW

Overall efficiency on carrier = 33 %
Overall efficiency 100 % mod. = 37·5 %

Harmonic distortion

Tone frequency 400 c./sec. Depth of modulation	R.M.S. harmonic content
50 %	1·7 %
70 %	1·7 %
90 %	2·0 %

Frequency Response

— 1 db. at 50 c./sec.
0 db. at 1 000 c./sec.
— 1 db. at 8 000 c./sec.
— 2 db. at 10 000 c./sec.

Noise-Level.—The r.m.s. value of the noise due to amplitude modulation was found to be 65 db. below 100 % modulation when the h.f. amplifier filaments were heated by direct current.

(d) Transmitter Power Supplies, Auxiliary Plant, and Control Circuits

The anode power supply for the high-power valves in all three transmitters which have been described is derived from continuously evacuated steel-tank mercury-vapour rectifiers. These rectifiers are similar in general design to those installed at the Droitwich Station, but minor improvements have of course been incorporated. The Droitwich rectifiers were described in detail in the paper read before The Institution, entitled "The Droitwich Broadcasting Station."* It is therefore not proposed to give a further description in this paper.

Five rectifiers were installed, foundations being put down for an additional rectifier to cover the possibility of the installation of a fourth transmitter in this building.

Each rectifier is designed for an output of 400 kW at any voltage between 14 000 and 22 000. As in the case of the Droitwich equipments, control is effected by induction regulators in the primary of the rectifier transformer. The primaries of the rectifier transformers are supplied at 415 volts, 3 phase, from a low-voltage switchboard of the flat-back type, situated in the same room as the rectifiers. A 3-phase, line-contact type contactor and an oil switch are mounted on the switchboard for the control of primary supplies.

Both the contactor and the oil circuit-breaker are controlled from the control desk of the transmitter to which the output of the rectifier is connected. The d.c. output of the rectifiers is taken to a totally enclosed switchboard, also situated in the rectifier room, on which are mounted air-break isolator change-over switches arranged in such a manner that any one of the five rectifiers can be switched to any one of the three transmitters.

Switchgear is also provided for a fourth transmitter and an additional rectifier. Auxiliary switches, which change over the control circuits, are coupled to the isolators.

(e) Filament Heating, Grid Bias, and Auxiliary Anode H.T. Supplies

The above supplies are all obtained from motor-generators, with the exception of filament-heating current for the modulators in the Marconi transmitter.

Motor-generators are provided in duplicate for each transmitter. These machines are situated in the auxiliary machine rooms which form the wings of the main transmitter building (see Fig. 22). The generators are driven by 3-phase induction motors controlled by contactor-type starters, and the output of the generators is controlled by contactors. These contactors are the only switchgear interposed between the generator and the load, and are used for selecting generators; they are designed to be capable of clearing a dead short-circuit. They are therefore fitted with solenoid-type overload trips. Both the motor starters and the output contactors are operated by switches situated on the control table.

Motor-operated field regulators are mounted near the contactors, which are also operated from the control tables.

Space does not permit enumeration of the outputs or other particulars of these motor-generator sets.

(f) Valve Cooling

Following normal practice, the cooling medium for the anodes in all transmitters is distilled water. In the case of the Marconi transmitter, cooling water is also used for the filament seals, and in addition compressed air is used for cooling the glass envelope of the valve, certain parts of the transmitter, and the anodes of the radiation-cooled valves in the r.f. amplifier which uses ACT.9 valves. In the Standard transmitters the glass envelope of the valves is not cooled except by natural means, and the cooling of the filament seals is effected by fitting radiator fins having a large area to the filament-seal connections. In the case of both transmitters, in spite of the large current flowing through the filament seal, which is due to the sum of the filament heating current and the r.f. circulating current, no trouble whatsoever has been experienced.

For the main cooling the distilled water in both transmitters circulates in a completely closed system; that is, at all times whether the water is in circulation or not, the water cooling system is completely full of

* *Journal I.E.E.*, 1935, vol 77, p. 437.

water, the difference in volume existing between hot and cold conditions being taken up by header tanks which are mounted on the roof. In this way the access of air is reduced and the consequent aeration of the distilled water kept to a minimum. As is well known, distilled water absorbs air very readily, and the aeration of the water considerably increases the corrosion which may be caused by the water.

The heat dissipated on the valve anodes is extracted from the cooling water by means of air-cooled radiators which are mounted outside the building. In the case of the Marconi transmitter the radiators are rated to dissipate 330 kW with a water flow of 130 gal. per min., and in the case of the Standard transmitters to dissipate 225 kW with a water flow of 160 gal. per min.

Individual electrically-operated water-flow alarms are provided for each of the high-power valves in the various transmitters. The operation of these water-flow alarms removes the anode and filament power from the valves concerned.

Electrically-operated water stills are provided for the make-up water for the valve cooling system.

(g) Central Crystal-Drive Room

It became apparent in an early stage of the development of this station that centralization of the crystal-drive equipment would be advisable. The fact that 6 transmitters were in operation and that further transmitters would be installed in the future, coupled with the necessity for driving two or three transmitters at the same carrier frequency, made such a scheme almost essential.

The crystal oscillators and harmonic generators associated with the two Standard transmitters were therefore used as a nucleus for the equipment of a central crystal-drive room, while the crystal-drive equipment and harmonic generators associated with the Marconi transmitter were held in reserve for special purposes. The equipment was erected in a room which was set apart for the purpose when the station was planned, and consists of 11 crystals in duplicate, two variable-frequency oscillators, and 10 fixed and 2 variable harmonic generators. Facilities are provided for the installation of an additional 4 fixed harmonic generators.

All transmitters on the site are connected to the crystal-drive room by means of cables which are fed from the outputs of the harmonic generators at carrier frequency. A selector switchboard has been provided in order that any harmonic generator may be connected to any transmitter. Provision has also been made for one harmonic generator to feed up to 4 transmitters. The outputs of the harmonic generators feed into attenuators which have been designed in such a manner as to permit any number up to 4 transmitters to be connected to one channel without affecting the output impedance of the harmonic generator. By a similar selector panel, any crystal output can be fed to any harmonic generator. All power supplies for this equipment are derived from rectifiers, which are provided in duplicate.

(8) POWER SUPPLY

The power supply for all transmitters at this station is obtained from the mains of the Northampton Electric Light and Power Co., Ltd., at 11 000 volts, 3 phase, 50 cycles. Emergency generating plant has also been installed to cover the possibility of a breakdown of the Company's mains. This consists of two 500-kW Diesel generating sets.

The Power Co. has provided a ring main which is looped into the main substation on the site. For a large portion of the route, underground cable is used; this is, of course, essential in the vicinity of the site owing to the nature of the overhead works. On the cable sections of the route Callender–Hunter split-conductor protection is used. This appears to be a satisfactory form of protection, in that one side of the ring main is frequently cleared without seriously affecting the station supply. Each side of the ring main is coupled to the high-voltage busbars in the substation by an oil circuit-breaker having a rupturing capacity of 250 000 kVA. From these busbars are fed two 2 500-kVA outdoor-type transformers, the secondaries of which are star-connected and coupled through oil circuit-breakers to the 415-volt busbars in the low-voltage switch-room.

The three older transmitting buildings on the site are each provided with separate substations, which are supplied from a duplicated feeder from the main substation. The main substation is equipped with truck-type switchgear, which was manufactured by the General Electric Co., Ltd., who supplied also the main transformers.

All plant in the new station is supplied at 415 volts, 3 phase. This system was adopted in preference to the system frequently used on the Continent, in which the item of plant which absorbs the major portion of the power, i.e. the anode H.T. converting plant, is supplied directly from the 11 000-volt system, while the auxiliary machinery is supplied by a small step-down transformer. Such a system possesses advantages in that it is slightly more efficient and requires transformers of sufficient capacity to feed only the auxiliary plant, but in the case of the Daventry Station it was found that the cost of the high-voltage switchgear suitable for controlling the input to 6 rectifiers would, to a great extent, offset the advantages of the system. Further, the alternators of the emergency power plant were not of a size which could be conveniently wound for 11 000 volts, and additional transformers would be required to couple them to the 11 000-volt system. The system of transforming all incoming power to 415 volts was therefore used, and although it involves the use of heavy-current switchgear and cables, experience shows that it is a satisfactory system.

The 415-volt 3-phase supply is controlled by a switchboard in the low-voltage switch-room, which is part of the substation. This board is of the flat-back type and carries equipment for controlling the output of the two 2 500-kVA transformers and the alternators of the emergency Diesel generating sets.

The power for the transmitters situated in the main building is conveyed by two 4 000-amp. feeders, which run from this switchboard by a short route to a similar low-voltage switchboard in the rectifier room, the latter switchboard being used for the control of the input to the mercury-vapour rectifiers. These feeders are not provided with circuit-breakers at either end but are controlled by isolators; they are, in fact, to be regarded as

an extension of the low-voltage busbar system, ample protection being afforded by the transformer circuit-breakers and the circuit-breakers controlling the individual mercury-arc rectifiers.

In addition to the 415-volt 3-phase supply required for the transmitters, a small proportion of single-phase load is required for lighting and small appliances. This is provided from the neutral of the star-connected transformers.

A d.c. supply at 230 volts has also been provided for the purpose of exciting the fields of generators, energizing control circuits, and for emergency lighting. The latter is provided to cover the period between the cessation of the Company's supply and the starting-up of the emergency power plant. It will be appreciated that a certain proportion of emergency lighting is essential in a building which is so large and contains so much complex plant. This supply is obtained from two motor-generators situated in the low-voltage switchroom; a 500-Ah storage battery is also provided. The switchboard in the substation has mounted on it equipment for controlling both the motors and generators of these sets and the battery.

The voltage of the d.c. system is controlled by two Brown-Boveri regulators which operate on the fields of the d.c. generators.

The emergency plant consists of two 500-kW Diesel generating sets, each engine being rated at 750 h.p., 375 r.p.m. The engines are of the 6-cylinder solid-injection type and are coupled to 415-volt, 50-cycle, 3-phase alternators. The engines and alternators are similar in many respects to those installed at the Droitwich Transmitting Station, but the fluctuating load imposed by the Class B system of modulation necessitated certain modifications, which are mentioned at the end of this Section.

The two 4 000-amp. feeders already mentioned, which are used for the purpose of feeding the transmitters in the main building, are terminated in the rectifier room on a flat-back type switchboard. This switchboard controls the main primary and auxiliary power inputs to the 5 rectifiers, additional panel space being provided for a sixth rectifier. All auxiliary supplies for the transmitters are controlled from a smaller switchboard.

In addition to the main feeders, a 3-phase service cable is also brought in from the substation. This is used for supplying lighting and machinery for services in the building.

The use of modulators operating as Class B amplifiers on two of the transmitters, and the possibility of further transmitters of this type being installed, made it necessary to design the power supply to be capable of dealing with rapid fluctuations in load. It is well known that the Class B modulator system imposes a fluctuating load on the power supply, and that this load is liable to changes, the rate of which is limited only by the reactance in the system. The audio-frequency alternating-current components in the anode circuit of the modulators are absorbed by the smoothing filters, but there appear in the power supply rapid changes of mean load with superimposed fluctuations at syllabic frequency. The condition can best be demonstrated by taking as a simple example the case of a commentator speaking with a steady crowd noise as a background. The crowd noise will represent a steady modulation which will show up on the power supply as a steady increase in load, while the commentator's speech will be represented by fluctuations at syllabic frequency.

In the case of the Daventry station the designers had to consider the conditions when the supply was derived from the mains or from the emergency generating plant.

With regard to the mains, these were of fairly low reactance and no trouble was anticipated due to the load fluctuations. This has been borne out by subsequent experience.

With regard to the emergency generating sets, the capacity of which was relatively small, it was necessary to give careful attention to the problem since variation of voltage or frequency would affect not only the linearity of the transmitters but also the stability of filament heating, grid bias, and other auxiliary supplies.

The load increment to be dealt with was of the order of 34 %. Taking, for example, a transmitter which at zero modulation imposes a load on the mains of 240 kW, this will increase to 321 kW when 100 % modulation is applied.

Table 4

ALTERNATOR REGULATION (SPEED AND EXCITATION CONSTANT)

	Power factor		
	Unity	0·8 lag	0·85 lag
Full load to no load			
Droitwich ..	11 %	29·5 %	
Daventry ..	2·5 %	—	12·5 %
No load to full load			
Droitwich ..	20 %	65 %	
Daventry ..	3·5 %	—	21·5 %

Assuming that two engines having a total output of 1 000 kW are supplying three transmitters, then the carrier load will be of the order of 720 kW and the peak load 963 kW.

Dealing first with the electrical side of the problem, it is apparent that the alternators must have good inherent regulation because no regulator can make the alternator fields respond in time to compensate for the rapid fluctuations of load. To this end, the alternators were designed to have a better inherent regulation than is normal, and steps were taken to keep the power factor of the load as near to unity as possible.

Table 4 gives the regulation figures obtained from the Daventry alternators as compared with those installed at Droitwich, which were of the ordinary commercial type, because the latter transmitter imposed a steady load on the power plant.

To maintain a power factor approaching unity, static condensers were connected across the mains. These are divided into groups, one group being associated with each transmitter. The switching is arranged in such a manner that a bank of condensers is brought into circuit when the auxiliaries serving that particular transmitter are started up.

In order to compensate for load changes of the ordinary

type, i.e. due to the switching on and off of transmitters and auxiliary plant and for slow changes in mean load due to modulation, a Metropolitan-Vickers regulator, operating on the fields of the alternator exciters, is provided. Here again a fairly rapid response was advisable and it was found that if the exciter fields were fed from a separate source the response time could be reduced by approximately one-half. The following figures were obtained on test:—

Time to increase alternator voltage from 100 % to 110 % of normal voltage:—

Self-excited ..	1·1 sec.	Open-circuit
Separately excited ..	0·6 sec.	

With regard to the engine, it was desirable to smooth out the rapid load fluctuations, leaving the engine governors to deal with relatively low-period fluctuations only. The engines were therefore fitted with flywheels of greater weight than is normal, and this, together with the unusually heavy alternator rotor, provided a sufficient energy storage for the purpose.

The following are comparative figures for the Droitwich and Daventry engine flywheels:—

	Weight tons	Kinetic energy at 375 r.p.m. ft. lb.
Droitwich ..	4·5	1 016 000
Daventry ..	5·8	1 750 000

(9) SPEECH INPUT EQUIPMENT

(a) Programme Chain

All programmes to be radiated are received from London over Post Office music circuits. The general routing of these programmes is shown in Fig. 30. It will be seen that each incoming music circuit is terminated with an equalizer which is adjusted to correct any frequency distortion present in the line. At this point the programme level is approximately 12 db. below "zero volume."*

The programme chain within the control room consists of a "B" or controlling amplifier followed by a number of "C" amplifiers, of which one is associated with each transmitter. There are 6 "B" amplifiers each preceded by a controlling potentiometer, so that a maximum of 6 separate programmes could be controlled and radiated if necessary. Normally the programme is controlled at the studio premises in which it originates, and only an occasional adjustment is required at the transmitting station. The output from any equalizer can be connected to the controlling potentiometer associated with any "B" amplifier (see Fig. 30). The programme level at the "B" amplifier output is zero, and a programme meter amplifier is connected across this point for visual monitoring.

Each "C" amplifier is fitted with a volume control which is so set that when the "C" is connected to any "B" amplifier output the transmitter is correctly modulated. The average level at "C" output is + 4 db.

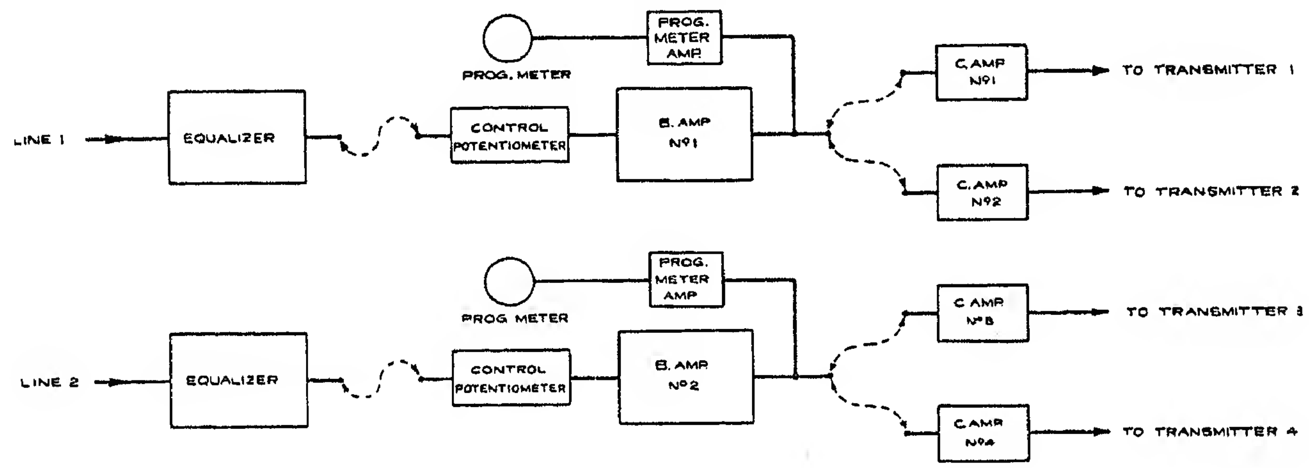


Fig. 30.—Schematic of control-room programme circuits at Daventry.

(b) Control-Room Power Supplies

The control room is operated entirely from mains supplies, the 415-volt 3-phase mains voltage being converted by means of rectifiers and suitable smoothing into 4 volts (d.c.) for filament heating (indirectly heated valves being used throughout), 250 volts (d.c.) for H.T. supplies, and 24 volts (d.c.) for switching relays, etc.

(c) Other Apparatus

There is an acoustically treated room which is normally used for quality checking; in this it is possible to make a direct loud-speaker comparison between the quality of the programme entering any transmitter and the programme leaving it. This room can also be used as a gramophone recital studio for the purpose of engineering tests.

The control room is also equipped with full audio-frequency and line-testing apparatus.

(10) COMMUNICATION SYSTEM AND MAST AND SITE LIGHTING

(a) Communication System

In view of the extent of the aerial system and the size of the main building, it was considered advisable to provide a telephone system for rapid communication between all vital points. A supervisory table was therefore provided in the centre of the main transmitting hall, and on this table is installed a telephone switchboard which connects to telephone points situated on each transmitter control desk, the l.f. control room, central

* Zero volume is defined as that volume of programme which will give a maximum deflection during loud passages on a meter calibrated to read maximum on a tone of 1 000 c./sec. at zero voltage level, i.e. 0·775 volt r.m.s.

Table 5

TYPICAL SIGNAL-TO-NOISE MEASUREMENTS MADE AT CANADIAN BROADCASTING CORPORATION RECEIVING STATION, OTTAWA

Transmission	Period (G.M.T.)	Call sign and frequency (Mc./sec.)	Aerial No. and power	Signal-to-noise ratio	
					db.
4A	1815–2100 July and August, 1938	GSG; 17·79	Aerial 1, 10 kW	Average	33
				Maximum	44
				Minimum	18
4B	2115–2300 July and August, 1938	GSP; 15·31	Aerial 3, 50 kW	Average	36
				Maximum	42
				Minimum	14
5	2320–0130 July and August, 1938	GSD; 11·75	Aerial 4, 10 kW	Average	34
				Maximum	42
				Minimum	No signal

drive room, and to an outdoor instrument situated midway between each pair of masts. An instrument is also provided near the aerial selector switches.

By means of this system the supervisory engineer is able to control all operations on the site. A little consideration will show that such a telephone system is essential to the proper organization of wave-change operations, and to the rapid clearing of any fault which may develop on the aerial system.

(b) Mast and Site Lighting

The masts on the site are lighted with red obstruction lamps in accordance with the requirements of the Air Ministry. It was thought necessary also to light the concrete paths which give access to the switching systems at the base of each aerial. In addition, floodlights are provided which can be used to light the feeder switching system at the base of each aerial, in order that urgent repair work may be carried out during the hours of darkness. Floodlights are also provided on the selector switches and aerial switching frame.

To supply these lights an armoured cable was laid alongside the concrete paths, from which the various lighting points on the masts and lamp posts were tapped off. Owing to the great expense a single feeder only was used, which is controlled by a switch in the low-voltage switch-room in the substation.

Isolator switches were provided at the base of each

Table 6

TYPICAL RECEIVED FIELDS MEASURED BY RADIO CORPORATION OF AMERICA, RIVERHEAD, NEW YORK

Transmission	Period (G.M.T.)	Call sign and frequency (Mc./sec.)	Aerial No. and power	Total input signal to receiver	
					μV
4A	1815–2100 May and June, 1938	GSG; 17·79	Aerial 1, 10 kW	Average	770
				Maximum	6 950
				Minimum	11
4B	2115–2300 May and June, 1938	GSP; 15·31	Aerial 3, 50 kW	Average	3 220
				Maximum	22 000
				Minimum	301
5	2320–0130 Feb. to May, 1938	GSD; 11·75	Aerial 4:— until 26th Feb., 10 kW from 26th Feb., 50 kW	Average	8 420
				Maximum	30 000
				Minimum	280
5	2320–0130 Jan. to April, 1938	GSC; 9·58	Aerial 5:— until 25th Feb., 50 kW from 25th Feb., 10 kW	Average	7 000
				Maximum	34 000
				Minimum	165

NOTE: It is believed that the effective height of the Riverhead aerials is 10 m., in which case these figures would represent a maximum field strength of 3·4 mV/m.

mast to enable the mast circuits to be isolated in the event of a defect or for periodic maintenance work on the lighting fittings.

in each of the main areas the station was intended to serve. In a short-wave broadcasting service where reception is on ordinary commercial receivers in listeners' homes, such series of measurements are manifestly impossible. Nevertheless, some measurements have been made in a few places of the signal-to-noise ratio, or of the signal voltage produced by the carrier wave at the input terminals of the receiver.

Representative measurements are given in Tables 5–12. In each case the figures refer to the optimum wavelength during transmissions directed to the area in question.

Table 7

TYPICAL RECEIVED FIELDS IN BUENOS AIRES, MEASURED BY TRANSRADIO

Transmission 4B: GSO, 15·18 Mc./sec., Aerial 14, 10 kW, 2115–2300 G.M.T.

Date (1938)*	Total input to receiver (μV)
February 21	3 800
February 21	6 500
February 22	6 000
February 22	4 500
April 16	8 000
April 17	7 000
April 18	8 500

Transmission 5: GSB, 9·51 Mc./sec., Aerial 13, 50 kW, 2320–0130 G.M.T.

Date (1938)*	Total input to receiver (μV)
February 7	3 200
February 19	3 800
February 19	3 000
February 22	6 800
February 22	6 200
February 22	5 000
March 14	7 000
March 14	15 000
March 14	8 400
March 31	7 300
March 31	7 500

* The dates were selected by the measuring organization.

Table 8

SIGNAL-TO-NOISE RATIOS MEASURED BY A PRIVATE LISTENER IN SALISBURY, SOUTHERN RHODESIA* (AMERICAN R.M.E. 69 RECEIVER)

Transmission 2/3 GSH, 21·47 Mc./sec., Aerial 23, 50 kW, 1042–1700 G.M.T.	Transmission 4A GSG, 17·79 Mc./sec., Aerial 19, 50 kW, 1720–2100 G.M.T.	Transmission 4A GSD, 11·75 Mc./sec Aerial 16, 50 kW, 1720–2100 G.M.T.
Weekly averages: 11 June to 13 August, 1938	Weekly averages: 30 April to 13 August, 1938	Weekly averages: 30 April to 13 August, 1938
db.	db.	db.
41–45	43	35
42–51	44	39
43–53	47	42
41–45	51	43
45–49	52	46
40–51	53	44
44–46	51	46
39–51	48	45
38–47	44	44
40–49	48	45
	47	42
	50	47
	48	43
	45	43
	46	41
	40	44

* The figures represent the average value of the carrier above the peak total noise input to the receiver with the aerial connected.

(11) PERFORMANCE OF THE STATION

A comprehensive specification of the performance of a short-wave broadcasting station which is received entirely by indirect radiation propagated through the ionosphere would require a series of curves to be established, showing the percentage of time during which the overall signal-to-noise ratio had exceeded given values

Table 9

TYPICAL RECEIVED FIELDS MEASURED BY EGYPTIAN STATE BROADCASTING AT MAADI, CAIRO

Transmission	Period (G.M.T.)	Call sign and frequency (Mc./sec.)	Aerial No. and power	Field strength (microvolts per metre)	Signal-to-noise ratio (db.)
4A	1720–2100 June to August, 1938	GSI; 15·26	Aerial 25, 10 kW	Average 153 Maximum 320 Minimum 32	Average 28·0 Maximum 30·0 Minimum 26·0
4A	1720–2100 December, 1937, to March, 1938	GSB; 9·51	Aerial 21, 10 kW	Average 708 Maximum 3 170 Minimum 178	Average 28·6 Maximum 30·0 Minimum 26·0

Insufficient measurements are available to permit the information to be given in the form of curves. The aerial number refers to the list of aerials given in the paper, and the transmitter power is indicated.

The figures in Tables 5–12 give some quantitative information as to the performance of Daventry. Qualitatively, it can be stated that experience shows that it is now only on rare occasions of exceptionally disturbed ionospheric conditions that it is impossible to receive the news bulletins from Daventry, on a reasonably good commercial receiver, in any part of the world, at least once every 24 hours.

(12) FURTHER DEVELOPMENTS

As indicated in an earlier Section of the paper, it has been found necessary to install two additional transmitters and several additional aerials for the purpose of providing foreign language broadcasts.

The two transmitters which have been ordered have high-frequency circuits similar in every respect to those of the Marconi transmitter which has been described, but the modulation circuits have been redesigned and are now of the Class B type. Additional rectifiers have been installed for the main H.T. supply, while the auxiliary supplies are obtained from motor-generators, the general arrangement being similar to that adopted for the other transmitters.

Extra aerials are being provided as shown in Table 11.

Table 11

Aerial No.	Working on	Designed wave, in metres	Bearings, in deg. E. of N.	Reflector	No. of hor. $\frac{1}{2}\lambda$ elements	No. of vertical stacks	Height of bottom stack above earth, in wavelengths
26	GSV	16·84	16/30 196/210/224	RR slewable	4	4	1
27	GSF	19·818	,,	RR slewable	4	4	1
28	GSC	31·32	,,	RR slewable	4	4	1
29	GSO	19·763	80/260	RR	4	4	1
30	GSC	31·32	80/260	RR	4	4	1

Aerials 26, 27, and 28 are being carried between Mast E and a new 250-ft. mast (see Fig. 14). Aerials 29 and 30 are being erected in Bay AB in the space originally designed for aerial No. 11. Suitable additions are being made to the feeder system and the feeder-switching frame.

Table 10

OBSERVATIONS AS TO SUITABILITY FOR RE-BROADCAST MADE AT MONT PARK, MELBOURNE, RECEIVING STATION OF POSTMASTER-GENERAL'S DEPARTMENT, COMMONWEALTH OF AUSTRALIA

Transmission 1: { GSD, 11·75 Mc./sec., Aerial 10, 50 kW

April, 1938

Percentage of Total Time Observed	
Excellent	29·1 %
Good	62·2 %
Satisfactory	5·8 %
Poor	2·9 %
	100·0 %

July, 1938

Percentage of Total Time Observed	
Excellent	36·4 %
Good	59·2 %
Satisfactory	4·4 %
Poor	0·0 %
	100·0 %

Table 12

MEASUREMENTS ON DIRECTIVITY OF AERIALS MADE AT YAMACHICHE RECEIVING STATION OF CANADIAN MARCONI COMPANY*

Date (1937)	Ratio of carriers db.
July 28	20
July 29	18
July 30	20
August 2	20
August 3	26
August 9	28
August 10	28

* The figures show the attenuation which had to be introduced into circuit in order to produce the same output when, on GSG, 17·79 Mc./sec., an aerial directional on Canada (aerial No. 1) was substituted for an aerial directional on Africa (array No. 19), using the same 50-kW transmitter. This condition actually represented a change from Transmission 4A to Transmission 4B.

ACKNOWLEDGMENTS

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APPENDIX

Wavelength Bands available for Short-Wave Broadcasting Services

The following wavebands were allotted for short-wave broadcasting in the radiotelegraph regulations annexed to the Radiotelegraph Convention signed at Washington in 1927:—

6 000 to 6 150 kc./sec. (50–48·8 m.)
9 500 to 9 600 kc./sec. (31·6–31·2 m.)
11 700 to 11 900 kc./sec. (25·6–25·2 m.)
15 100 to 15 350 kc./sec. (19·85–19·55 m.)
17 750 to 17 800 kc./sec. (16·9–16·85 m.)
21 450 to 21 550 kc./sec. (14–13·9 m.)

Up to that time there were no specific allocations of wavebands in this part of the radio-electric spectrum, and stations—both broadcasting and the other services—worked on wavelengths which had been proved suitable by experience. There were but few broadcasting stations working on short waves in 1927, and the bands allotted to broadcasting did not do much more than accommodate the then existing stations. At that time a frequency separation of about 50 kc./sec. was considered necessary on short waves, and it was only by reducing this separation progressively as both transmitting and receiving technique improved that it became possible to accommodate the many short-wave broadcasting stations which subsequently were brought into service. No changes were made in these short-wave bands at the next conference, held in Madrid in 1932. The allocated spectrum was extended from 23 000 kc./sec. up to 30 000 kc./sec. (down to 10 m.), and of the additional spectrum 1 000 kc./sec. was given to broadcasting; so that the Madrid allocations were the same as those printed above, with the additional band of 25 600 to 26 600 kc./sec. (11·72 to 11·28 m.).

Since 1932 short-wave broadcasting has developed extremely rapidly, the position in 1937 being shown in Table 13. The inadequacy of the Washington and Madrid allocations is most striking. They provided for broadcasting only 3·6 % of the available spectrum between 1 500 kc./sec and 25 000 kc./sec. By way of comparison, amateurs were allowed to work on frequencies representing 6·3 % of this spectrum, 2·9 % of which was exclusive and the rest shared with other services. The mobile services could work on 49 %, and the fixed service on 76 %.

These statistics, even taking into account the fact that the transmissions are not all simultaneous and that certain notified frequencies may never be used, reveal the real gravity of the situation of broadcasting on short waves.

Table 13

THE DEVELOPMENT OF BROADCASTING ON SHORT WAVES

Location	Number of waves used							
	in the bands allotted at Madrid				outside the bands allotted at Madrid			
	Jan. '36	Jan. '37	Apr. '37	Oct. '37	Jan. '36	Jan. '37	Apr. '37	Oct. '37
Africa	1	1	3	4	0	1	1	1
North America	21	27	27	28	0	0	0	1
Central and South America	19	32	37	40	45	68	71	84
Asia	0	5	4	8	0	8	7	5
Europe	28	40	44	47	6	17	20	24
Oceania	1	3	3	3	0	0	0	0
	70	108	118	130	51	94	99	115

Total: January, 1936 121
January, 1937 202
April, 1937 217
October, 1937 245

This was the position which faced the recent Telecommunications Conference held in Cairo in February and March, 1938. The International Broadcasting Union had proposed that each of the bands useful for long-distance broadcasting service (between 6 000 and 21 550 kc./sec.) should be extended to the uniform width of 300 kc./sec., and that certain bands between 1 500 kc./sec. (200 m.) and 6 000 kc./sec. (50 m.) should be made available for local services in tropical regions where the use of wavelengths in the medium waveband 1 500 to 550 kc./sec. (200 to 540 m.) was precluded owing to the high level of atmospherics. The Cairo Conference was able to satisfy the request of the broadcasting interests to a large extent, in so far as tropical broadcasting was concerned, but to a lesser (and, in the broadcaster's view, an inadequate) extent in the long-distance bands.

Table 14

ANALYSIS OF THE SHORT-WAVE BROADCASTING BANDS IN 1937

1. Band 6 000–6 150 kc./sec. (50–48·78 m.)	
Width of band	150 kc./sec.
Number of usable frequencies	16
Number of transmissions actually observed	50
Number of notified frequencies:—	
(a) broadcasting	164
(b) telegraphy	46
2. Band 9 500–9 600 kc./sec. (31·58–31·35 m.)	
Width of band	100 kc./sec.
Number of usable frequencies	11
Number of transmissions actually observed	27
Number of notified frequencies:—	
(a) broadcasting	93
(b) telegraphy	8
3. Band 11 700–11 900 kc./sec. (25·64–25·21 m.)	
Width of band	200 kc./sec.
Number of usable frequencies	21
Number of transmissions actually observed	22
Number of notified frequencies:—	
(a) broadcasting	82
(b) telegraphy	41
4. Band 15 100–15 350 kc./sec. (19·87–19·54 m.)	
Width of band	250 kc./sec.
Number of usable frequencies	26
Number of transmissions actually observed	21
Number of notified frequencies:—	
(a) broadcasting	64
(b) telegraphy	11
5. Band 17 750–17 800 kc./sec. (16·90–16·85 m.)	
Width of band	50 kc./sec.
Number of usable frequencies	6
Number of transmissions actually observed	5
Number of notified frequencies:—	
(a) broadcasting	29
(b) telegraphy	5
6. Band 21 450–21 550 kc./sec. (13·99–13·92 m.)	
Width of band	100 kc./sec.
Number of usable frequencies	11
Number of transmissions actually observed	5
Number of notified frequencies:—	
(a) broadcasting	24
(b) telegraphy	1
7. Band 25 600–26 600 kc./sec. (11·72–11·28 m.)	
Width of band	1 000 kc./sec.
Number of usable frequencies	101
Number of transmissions actually observed	0
Number of notified frequencies:—	
(a) broadcasting	14
(b) telegraphy	6

In these bands the following allocations were made:—

6 000 to 6 200 kc./sec. (50–48·39 m.), an addition of 50 kc./sec.
9 500 to 9 700 kc./sec. (31·58–30·93 m.), an addition of 100 kc./sec.
11 700 to 11 900 kc./sec. (25·64–25·21 m.), no change
15 100 to 15 350 kc./sec. (19·87–19·54 m.), no change
17 750 to 17 850 kc./sec. (16·90–16·81 m.), an addition of 50 kc./sec.
21 450 to 21 750 kc./sec. (13·99–13·79 m.), an addition of 200 kc./sec.
25 600 to 26 600 kc./sec. (11·72–11·28 m.), no change

The band 25 600 to 26 600 kc./sec., although allocated at Madrid, has not in fact been used for long-distance broadcast transmission, as waves of this order are propagated to long distances only in conditions of the ionosphere which occur relatively infrequently and for short periods round about the sunspot maximum years.

It will be noted that no frequencies were allotted for long-distance broadcasting at about 60 to 70 m., although proposals had been made to that effect. In withdrawing its proposals the British delegation did so on the understanding that objection would not be taken to the use of a suitable wavelength of that order by Daventry to provide a service to Canada at periods of the sunspot cycle when service could not be given on the shorter wavelengths (i.e. on frequencies above 6 000 kc./sec.) allotted to the broadcasting service.

No internationally agreed wave plan has been drawn up for short-wave broadcasting stations, and the frequencies at present used by these stations are those chosen by individual organizations as most likely to suit their own requirements. While an international wave plan may ultimately be necessary to avoid chaos, it appears that the time is not yet ripe and that a conference which endeavoured to produce such a plan in the limited wavebands available would be unlikely to succeed.

The frequencies notified to the Berne Bureau for use by Daventry are as follows:—

Frequency	Wavelength	Call sign	Remarks
kc./sec.	m.		
6 050	49·59	GSA	
6 110	49·10	GSL	
7 230	41·49	GSW	As from 1.9.39
7 260	41·32	GSU	As from 1.9.39
9 510	31·55	GSB	
9 580	31·32	GSC	
11 750	25·53	GSD	
11 820	25·38	GSN	
11 860	25·29	GSE	
15 140	19·82	GSF	
15 180	19·76	GSO	
15 260	19·66	GSI	
15 310	19·60	GSP	
17 790	16·86	GSG	
17 810	16·84	GSV	
21 470	13·97	GSH	
21 530	13·93	GSJ	
21 550	13·92	GST	
21 640	13·86	GSX	As from 1.9.39

DISCUSSION BEFORE THE INSTITUTION, 2ND FEBRUARY, 1939

Col. A. S. Angwin: In considering this paper on short-wave broadcasting, one is naturally led to make some comparisons with the problem of short-wave long-distance telephony. One interesting fact which emerges is that the experimental work which was carried out by the authors at Daventry, and the conclusions which were reached, followed almost the same course as investigations for long-distance short-wave telephony. In this case for long-distance telephony the horizontal type of short-wave aerial has been preferred, and has the advantage that it lends itself readily to adjusting the angle of propagation in the vertical plane and therefore to making adjustments according to the length of the transmission path.

I notice that the authors have evolved a new type of power distribution diagram, which gives some idea of the direction of radiation from the aerial. To my mind, the standard diagrams are the best for giving a picture of propagation in the vertical plane and in the horizontal plane, and I would ask the authors whether in fact they use such diagrams for their computations.

In 1931 the problem arose of making one set of aerials and one transmitter suitable for a telephony service to South America which had to be used partly to Buenos Aires and partly to Rio de Janeiro; these two centres of reception subtend at Rugby an angle of 5°. The principle of beam-splitting to divert the path of propagation in the horizontal plane was found to be most successful from the outset, and has since been in daily use. I should much like to know what is the actual width of the aerial which the authors describe on page 339, and for what purpose the method of slewing indicated is used in the Daventry broadcasting station. It is obvious that the wider the aerial system is made and the sharper the directed beam, the greater the difficulty is in slewing the aerial. What may be appropriate for a narrow beam for a long-distance telephony service may not be equally appropriate for a long-distance broadcasting service.

On page 346 it is suggested that the overall efficiency of the transmitters supplied by Standard Telephones and Cables, Ltd., is improved by the supply of high-frequency power from the penultimate stage to the aerial; but this seems to be at variance with the statement that there is no direct transfer of radio-frequency energy between the anode and the excitation circuits. I suggest that a new principle is involved here, and that it would be well if the authors would explain why it is of such great advantage. One of its advantages is that balancing condensers are not required in order to maintain stability, thereby eliminating one operation when changing the wavelength of the transmission.

The authors make some reference to the methods of drive of the transmitters, and it would be helpful if they would add data regarding the frequency stability with time of the Daventry transmitters.

It is perfectly true, as the authors indicate, that there is a very limited number of wavelengths available for broadcasting. At present there are 192 usable frequencies, and when the new regulations come into force there will be something like 243. At present the B.B.C. station at Daventry uses 16 frequencies, and it will shortly be using 19. Simple arithmetic shows that 13 other countries developing broadcasting on the same scale as we have in this country would completely monopolize every available frequency, unless recourse was had to some such expedient as sharing. In fact, there are 70 countries which belong to the International Broadcasting Union. Nearly all of them have claims on broadcasting, so that on that basis the problem is presumably insoluble. The B.B.C. have rightly built up their Empire and world broadcasting station on the assumption that it should be received by an individual with his own individual set, but I would suggest that this cannot be the ultimate solution. There seems to be no hope of obtaining the tremendous number of frequencies involved by every nation in the world broadcasting on every required frequency to every subscriber wherever he is situated, and the ultimate solution must lie in the direction, in some cases at least, of a point-to-point service, with all the facilities of a high-grade receiver, directional reception, re-transmission, and re-broadcasting. Such a service might make use of the single-sideband system with partially suppressed carrier, which, as indicated in the paper, is not immediately applicable for broadcasting; nevertheless, it makes possible a much better quality of reception from the point of view of fading and of signal/noise ratio. I suggest that the B.B.C. should experiment on these lines with a service to some British Dominion or Colony.

Mr. K. L. Wood: The paper is of great interest to point-to-point engineers, in that the broadcasting problem is so different from the point-to-point problem as to provide grounds for speculation as to how far such differences may be considered responsible for divergences in methods of operation.

Why is it preferable to distribute a large amount of power over a large area rather than take a smaller amount of power to a point and re-distribute it? If, as the authors suggest, point-to-point operation is so much easier than broadcasting and requires so much less power, would not it be better to adopt that process more fully?

We have a preference for the Franklin uniform vertical aerial for primary circuits supplemented by the Franklin series-phase aerial, which, being cheap and easily erected, lends itself to alterations with changing conditions.

Regarding the relative efficiencies of horizontal and vertical aerials, we have noticed in our experiments that the performance of the series-phase aerial varies a great deal with the nature of the ground. We have found that raising the aerial about 1 wavelength above the ground seems to get rid of this variation, and I should like to know whether the authors have experienced this effect.

Moving an aerial on Ascension Island only 150 yd. made an appreciable difference to the performance.

As regards reception, if receivers could have directed aerials, very much less power would usually be required. An exception to this occurs when the noise source is such that atmospherics and signals arrive from the same direction.

Turning now to the feeders, the authors say that it is due to cost, difficulty of maintenance, and various other factors, that they have given up using the concentric

type. On the long lengths of feeder we have had in use for 6–7 years the upkeep is almost nil; the only maintenance work which has been necessary has been the painting of the supports to keep them from rusting. The feeders are of $3\frac{1}{2}$ in. diameter and the power is up to 30 kW: we have had no flashovers from standing waves, and the switching from one aerial to another can be done inside the building very conveniently and efficiently. I realize the difficulties which are likely to occur as the power is increased, and I should like to know whether the authors have experienced any modulation of one transmitter by another due to the use of open feeders.

In the paper little is said about the upkeep of the Daventry transmitters, aerials, and feeders. We have at one station 11 short-wave and 5 long-wave transmitters and some 30 aerials, of which 5 are long-wave and 16 directional short-wave, covering a large acreage. Three men per watch do all the necessary switching for these transmitters, the rigging staff consists of eight men, and fourteen workmen are available for general purposes. The station is open continuously.

It would be interesting to know how these figures compare with the corresponding ones for the Daventry station, with its high-power transmitters.

I notice that at times three Daventry transmitters are working simultaneously on wavelengths which differ very little sometimes on the same programme. Has the suggestion been considered of working all three on one wavelength, so as to economize wavelengths where there is congestion?

Mr. H. Bishop: I notice in the advance copies of the paper a statement* which implies that the zonal basis of transmission which was part of the 1932 scheme has been abandoned. This is not the case, for the B.B.C. is still directing transmissions to particular parts of the world. It is true, however, to say that the tendency now is for transmissions to be arranged in the best listening periods.

In the short-wave field there is so much competition for the ear of the listener that it is essential to use the maximum power consistent with economic and operating considerations. On the other hand, particularly on economic grounds, if for no other reason, there is a limit to this line of progress, and eventually there must come an international agreement on power limitation. This question would be made simpler if there were more chance of world-wide legislation to suppress electrical interference, a step which would greatly help reception and as a consequence make the transmitting position easier.

The number of short-wave transmitters already existing and projected is far greater than the number of channels likely to be available, even allowing for what the broadcasting interests have obtained from the Cairo Telecommunications Conference. I think there will be advances, as time goes on, in the sharing of wavelengths. The problem is not an easy one, and the same criteria are not applicable over all the short-wave broadcast bands. On wavelengths between 17 and 31 m., which have world-wide coverage, the problem is difficult; but on wavelengths below 17 m. and above 31 m., where there is not necessarily world-wide propagation, the sharing of waves may have to come into more general use.

Another aspect of the same problem which may tend to ease the situation is the synchronization of one or more transmitters in a particular country sending out the same programme in different directions. This has been done at Daventry. On page 350 it is stated that up to four transmitters can be connected to one channel, but I think that so far only two transmitters have been so connected.

The problem of deciding the narrowness of beams to be used is a complicated one. If a beam is made half as wide as it is now, it is obvious that to cover the same area it is necessary to have twice as many transmitters, and, what is more important, twice as many aerials and twice as much land. Furthermore, each aerial will be twice as wide.

The system in use at the German short-wave station at Zeesen might have been described by the authors in more detail, to enable a comparison to be made with what has been done at Daventry. I think also that the authors might tell us something about the rotating mast system which has been erected in Holland.

I am sorry that the authors do not mention the importance, from the operating point of view, of a high-power modulation system. Where it is necessary to make rapid changes of wavelength several times a day, it is of extreme importance that the number of adjustments should be as few as possible. In this respect the high-power modulation system compares very favourably with the low-power system in that with the former only one set of circuits has to be changed, and it does not matter much if the other circuits are not exactly in tune.

The B.B.C. was very dependent in the early days on reports of reception sent by enthusiastic amateurs from all over the world, many of whom used directional receiving aerials. It would have been of interest if the paper had dealt with the use of such aerials by the ordinary listener.

Finally, it is interesting to note that experience at Daventry has confirmed the success and efficiency of Class B modulation.

Mr. E. K. Sandeman: In Figs. 8 to 11 of the paper the authors give four power distribution diagrams, showing the relative power density radiated by the four types of aerials over one half of the hemisphere above the horizon. When looking at these diagrams one can imagine that one is standing at the aerial, looking forward in the direction the aerial is required to radiate, and the radiation in the half-hemisphere in front is represented by means of contour lines of equal power density, to an arbitrary scale such that the peak power density is represented by the figure 100. Since no reflector is used with these particular aerials, the radiation into the hemisphere behind is exactly the same as that in front. Everywhere on the chart equal solid angles subtended at the aerial are represented by equal areas. For this reason, in addition to portraying a solid polar diagram on a flat surface, the chart enables the directivity to be calculated by graphical integration of the power density over the area of the chart. In the case of an aerial radiating uniformly in all directions, the directivity is evidently unity, because the directivity is defined as the peak power density divided by the mean power density.

Since the paper was written, it has been shown that these diagrams also provide a means of portraying the

* Revised for the *Journal*.

absolute value of ϵd per $\sqrt{\text{kW}}$. The simple formulae required for this purpose can be derived as follows:—

Let P_c = arbitrary marking of power-density contours on chart (such that $\hat{P}_c = 100$);

K = a constant peculiar to each antenna, for converting contour markings into watts per solid radian per kilowatt radiated;

$P_r = KP_c$ = power density at each contour, in watts per solid radian per kilowatt radiated;

a = area on chart, in square inches; and

A = area of chart, in inches, corresponding to 4π radians = 4 × area of chart shown in Figs. 8–11.

Then, by definition, the directivity is given by

$$\delta = \frac{\hat{P}_r}{\frac{1}{4\pi} \times 1\,000} = \frac{K\hat{P}_c}{\frac{1}{4\pi} \times 1\,000} = \frac{100K}{\frac{1}{4\pi} \times 1\,000} = \frac{4\pi K}{10}$$

$$\therefore K = \frac{5\delta}{2\pi} \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

Also, by definition, the directivity

$$\delta = \frac{\hat{P}_c}{\frac{1}{A}\int_0^A P_c da} \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

Equation (2) describes how δ can be determined graphically, or in simple cases by calculation. Inserting in equation (1) the value of δ so determined, gives the value of K.

Then ϵd per root kilowatt is given by

$$100\sqrt{\left(\frac{KP_c}{26\cdot 5}\right)} \text{ millivolts per metre} \times \text{kilometres per root kilowatt} \quad . \quad (3)$$

where d is the distance in kilometres along the radius vector drawn from the aerial to the point at which the field strength is required.

Equation (3) is derived as follows:—

$10^{-10}\dfrac{P_r}{d^2}$ = power density at distance d (in watts per square centimetre of space) normal to the direction of transmission

$= 2\cdot 65 \times 10^{-13}\epsilon^2$, where ϵ is the field strength in millivolts per metre.

$$\therefore \quad \epsilon d = 100\sqrt{\left(\frac{P_r}{26\cdot 5}\right)} = 100\sqrt{\left(\frac{KP_c}{26\cdot 5}\right)}$$

Mr. A. J. A. Gracie: On pages 346 and 349 are shown the efficiencies of two types of transmitter which are installed at Daventry. In the case of one type a carrier output of 80 kW at 30 % modulation, which is probably the average modulation, is obtained with a total power consumption of 258 kW; whereas in the case of the other transmitter it seems that the equivalent total powei for 80 kW carrier output is of the order of 460 kW. The difference in total power consumption between the two, therefore, is about 200 kW, which means that the power bill for one transmitter must be roughly £2 000 a year more than for the other. Are there any other factors, such as saving in capital cost, which justify the use of the transmitter which is the more extravagant in regard to power consumption?

The other point which I should like to raise is in connection with the wavelength question. Can the authors give any idea as to what percentage of the populations of the various Colonies and Dominions actually listens on short wavelengths? I think that the number of people in Britain who listen on short wavelengths, other than very occasionally, is very small. It seems to me that this question has an important bearing on whether one should broadcast to individuals rather than send to a fixed point on short waves and then re-broadcast on medium waves, as suggested by Col. Angwin.

Mr. J. A. Smale: I should like to refer to the " onion " diagrams sponsored by Mr. Sandeman. They show the optimum projection angle of the aerials dealt with to be 5° and 7·8° respectively from the horizontal. This seems an extraordinarily low angle of projection, and it may therefore be that the theoretical considerations expounded by Mr. Sandeman are modified in practice. Perhaps the authors could state what confirmation they have had of the angle of projection which is found to be the best. For an organization to have some standard aerial with which all other aerials can be compared is very useful. Seeing that the B.B.C. receive so many reports of reception it seems that they must have figures available which would enable them to quote the gains of various types of aerials, relative to their dipole aerial erected some 3·6 wavelengths above ground.

As regards slewed aerials, the difficulty is to change the direction of the diagram without distorting it; this requires that the phases should be changed in sufficiently small elements of the whole aerial. Where there are two horizontal dipoles side by side and the feed to those dipoles is changed by the theoretical amount, the main effect on the diagram is to distort it.

The authors state that 3 000 ft. of B.B.C. feeder operating at 18 Mc./sec. has a loss of 23 %, so that the two highest-frequency aerials, which are at the maximum distance from the station—one being at the distant end of one line of aerials and the other being the penultimate aerial of another line—must have a feeder loss of at least 40 % to 50 % at 23 Mc./sec. For these high-power transmitters, which, despite their excellence of design, must have lower conversion efficiencies at their higher frequencies, this represents a serious wastage of power. It would seem that quite a considerable capital expenditure would have been worth while if these higher-frequency aerials could thereby have been brought much nearer to the station.

I am interested in the authors' remarks on the subject of stub reactances. These are particularly suited to overhead 2-wire lines, which perhaps require adjustment of termination more often. In his verbal summary of the paper the author referred to a special bridge which had been developed for effecting the matching of aerials to feeders by means of stubs. Some more details of that method would be welcome.

Mr. E. Green: When the B.B.C. approached Marconi's Wireless Telegraph Co. with a view to the purchase of a 100-kW short-wave transmitter, we had a transmitter

capable of delivering 25 to 35 kW with rapid wave-change by means of revolving turntables. No valves capable of 100-kW output existed, although a short-wave version of the CAT.14 (the valve used at Droitwich on long waves) was projected, and it was calculated that a pair of these would easily give the output required. From previous experience it was realized that the vital point would be the grid seal, which at 13·5 m. had to carry a peak current of 250 amperes, with an r.m.s. value of over 120 amperes, with normal modulation.

Faced with this problem, the M.O. Valve Co. took the bold step of making the grid connection a complete ring with a glass seal on either side. They had their reward, for (when the initial manufacturing difficulties had been surmounted) the valve was trouble-free from the commencement.

On the transmitter it was decided to abandon turntables, and adopt circuit trucks. Circuits could be set up to optimum value, and no idle circuits remained in the panel to cause trouble. Any number of waves could be provided; idle trucks could be serviced, or set up to new waves while the transmitter was in operation; also tests with a single circuit would give reliable information as to final results. When it had been decided to adopt trucks, the problem of fitting them into the allotted space remained, and gave the designers some anxious moments. On the design side it is of interest to note that at 13·5 m. the possible peak value of current in the main anode circuit is about 700 amperes.

The figures given on page 346 are hardly fair to the system of series modulation adopted. This was intended to be used in conjunction with floating carrier, obtained by a very simple additional circuit. At zero modulation the carrier was reduced by 6 db., and increased linearly with the degree of modulation to give full carrier at 100 % modulation. With this system in operation on 49·6 m., for 100-kW carrier the figures for total input power varied from 300 kW at zero modulation to 480 kW at 100 % modulation. The distortion was less than 3 % below 50 % modulation, and less than 4 % from 70 % to 90 % modulation. When listening in England, it was not possible to tell whether the "float" was in operation.

The system has the advantage that the high-frequency parts of the system, the transmitter-feeders and aerials, are subjected to maximum stress only when this is required by the modulation.

Will the authors tell us why the use of floating carrier was abandoned?

I do not think the claim for increased overall efficiency of the inverted amplifier can be substantiated. There is no theoretical reason for it. On 31 m. on the conventional amplifier, for 100-kW output the total power supplied to the two last stages is 159 kW, giving 63 % efficiency, as against 64 % for the inverted amplifier.

Mr. A. J. Gill: The paper does not say whether the insulators described on page 333 are made of porcelain or of some other material. One naturally assumes that they are of porcelain, but they also look rather like a type of Pyrex-glass insulator which is sometimes used.

In the description of the anode supply the authors speak of a steel-tank mercury-vapour rectifier. One usually associates the term "mercury-vapour rectifier" with some device having a heated filament. Does that apply to this equipment, or is it what is usually known as a mercury-arc rectifier?

The descriptions of the new transmitters are interesting, and each method of construction appears to have its advantage. The truck system of changing wavelengths permits an unlimited number of changes to be made provided sufficient trucks (and sidings to accommodate them) are available. On the other hand, the truck system does not lend itself to such quick operation as the turret system, and for commercial-service telegraph and telephone transmitters where every minute is of importance from a revenue-earning point of view the turret system of wave-changing has been found entirely satisfactory.

Mr. H. L. Kirke: I should like to say a word in connection with the experiments on aerial design to which the authors refer. One of the great controversies which has been going on for many years in short-wave broadcasting, and which is now going on in ultra-short-wave broadcasting, is whether the polarization from the transmitter shall be horizontal or vertical. Our experiments at Daventry showed us quite conclusively that the horizontal polarization was the more efficient, and I believe that that has been borne out by others who have made controlled experiments; but no one, to my knowledge, has given any answer to the question why. Two possible suggestions occur to me. One is that the values of the reflection coefficient of the ground are different in the two cases, with the result that the power loss in the earth near the transmitter is less with horizontal than with vertical polarization. The other possible explanation is that it is usually necessary to series-feed vertical aerials, with the result that there is usually a phase-shift along the aerial which makes it impossible to get the correct phase-relation between currents in various parts of the aerial, and this may result in inefficiency.

Mr. R. M. W. Grant (*communicated*): On page 355 it is mentioned that two new transmitters have been ordered with high-frequency circuits similar in every respect to those of the Marconi transmitter but with Class B modulators. On page 357 it is stated that the series amplifier has the advantage of a high overall efficiency due to the utilization of the power delivered to the penultimate stage. Why has the advantage of this high overall efficiency been forgone by adopting for the two new transmitters the more conventional type of high-frequency amplifier used in the Marconi transmitter? Is it not so that the overall efficiency of the penultimate and the final amplifier when taken together is no better than in the conventional arrangement?

Let P = carrier power required, η_F = conversion efficiency of the final amplifier, and η_P = conversion efficiency of the penultimate amplifier. For the conventional type of circuit the power required from the H.T. source would be equal to

$$\frac{P}{\eta_F} + \frac{P_g}{\eta_P}$$

whereas for the series type the power required would be

$$\frac{P - E_g I_a}{\eta_F} + \frac{P_g + E_g I_a}{\eta_P}$$

Assuming that the same conversion efficiencies would be obtained in the two cases, the overall efficiency is the same whichever type of circuit be used. The real advantage of the series type lies, not in the efficiency, as the authors seem to imply, but in the fact that smaller valves may be used in the final amplifier; nevertheless, larger valves must be used in the penultimate amplifier. The question of relative merits therefore reduces to one of valve costs, and the authors may be able to give some data on this point.

In their verbal summary of the paper the authors announced that these two new transmitters had been put into service on the 1st February, 1939, and it would be interesting to learn whether sufficient data have been recorded to show a comparison in performance between the series-modulated and the Class-B-modulated versions of the same transmitter. Has it been found necessary to use negative feedback in the new transmitters to obtain response and distortion figures comparable with those given by the series-modulated type? It would be of interest to know the harmonic-distortion and frequency-response figures for the Standard transmitter when negative feedback is not used.

Mr. N. Wells (*communicated*): In connection with the tests of vertically and horizontally polarized aerials, although a large amount of patient and careful investigation has been undertaken by the B.B.C. it cannot be claimed that the results are conclusive, because, as is emphasized in the paper and as has been shown by Mr. T. L. Eckersley,* height is a major determinant in effective short-wave radiation under normal conditions. Had the overall height of the twin Franklin uniform aerials in Fig. 6 been brought up to the overall height of the stacked dipoles, by means of non-radiating feeders, I do not doubt that there would have been little to choose between the two polarizations. Polarization can hardly affect long-distance propagation, while height and energized area of curtain appear to be major factors when designing for *average* seasonal conditions.

The problem of concentric versus twin feeders is purely one of economics; doubtless there is something to be said in favour of the twin open feeder when carrying 100 kW to each of 25 aerial systems, but in 1925 when planning for the original Empire communications stations Mr. Franklin's main objects in originating the concentric feeder were stability and safety (a consequence of the low impedance and almost perfect screening), efficiency in relation to the amount of copper employed, and ease of maintenance under all weather conditions. A good deal of experience has been gained during the intervening years, and all goes to prove that the original design has been fully justified.

I must join issue on the question of ease of switching and cost of equipment, as between twin and concentric feeders. Fig. A illustrates an actual commutator for connecting any of 8 transmitters with any of 20 aerials. The 20 concentric aerial feeders are visible in the lower portion of the picture, and the 8 transmitter feeders, 4 a side, in the right-hand upper horizontal portion. Vertical marked rods, which can be rotated through 180°, give a quick connection as between each aerial and the 8 transmitters, while the easily-moved horizontal screening insulates the electrical fields from each other and completes the operation. The transmitters have been connected at one end in order to facilitate walking from front to back of the commutator. Obviously the arrangement is compact; it has the advantage of being operated from inside the station building, and I hope it will be conceded that it permits changes to be easily carried out. I believe that it is at least as economical to construct as the ingenious switching equipment described by the authors.

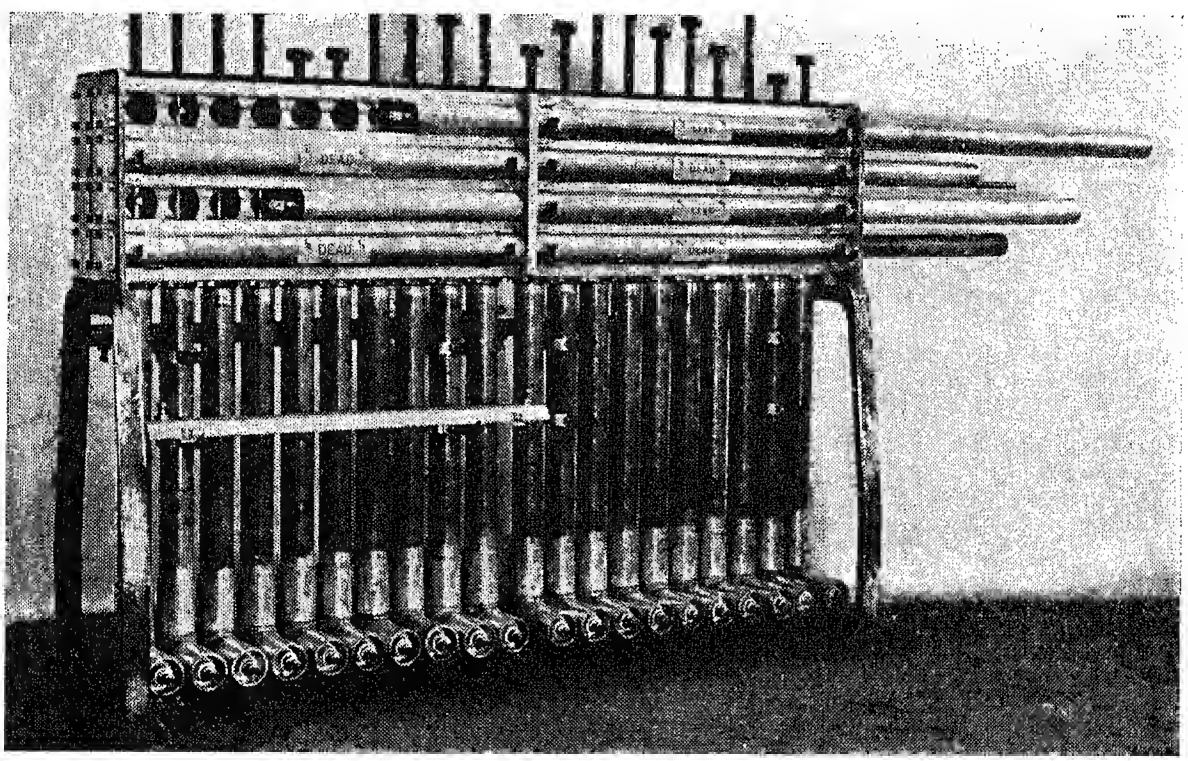

Fig. A

[The authors' reply to this discussion will be found on page 365.]

* "Radiation from a Short-wave Aerial," *Marconi Review*, August, 1930.

NORTH-WESTERN CENTRE, AT MANCHESTER, 31ST JANUARY, 1939

Mr. F. Jones: The paper has two main features: one is the rapid development which has taken place in a comparatively short time in the technique of short-wave broadcasting, and the other is the improvement in transmitter design. The circuit design of the high-power amplifier used in the standard transmitter is very ingenious. Stability of high-power amplifiers for wavelengths of the order of 15 m. is not easy to achieve; and this particular circuit not only improves the stability and efficiency but obviates the necessity for adjustment of balancing condensers.

The authors say that their turntable method of changing the wavelength permits the use of a spare valve. I should welcome further explanation of this point.

I notice that in the specification for their transmitters the B.B.C. showed a preference for high-power modulation. Do the authors consider that high-power modulation is better for short-wave transmission than low-power modulation, having regard to the fact that a lower overall efficiency is necessarily obtained with the former? In this connection I would say that when Class B modulation is used at high power the rapid variation of the load is a real difficulty, particularly where the emergency power supply is being used.

I notice two omissions from the paper. One is that whereas the output of the modulator carrier is quoted for both the transmitter and the modulator power at 100 % modulation, no statement is made as to what depth of modulation is customary for these transmissions. It would be interesting to know whether the B.B.C. use a standard depth of modulation, whether they vary the modulation to suit the varying conditions, or whether they are prepared to increase the power at certain times at the expense of quality. In their verbal summary of the paper the authors talked of the reception of speech being good in some places but music transmission proving a more difficult test; this seems to suggest that for music transmission the depth of modulation sometimes employed is actually less than for speech.

Prof. Willis Jackson: It is evident from the paper, and is in no sense a criticism of the authors, that the large amount of work which has been done of recent years in the attempt to clarify the changes which occur in the ionized regions of the upper atmosphere, while extremely valuable as an aid to explaining observed phenomena, has not gone very far as yet towards providing a satisfactory basis for the design of long-distance short-wave transmission systems. In this connection the observed superiority of the horizontal as against the vertical type of aerial array is striking, and to me rather surprising, and I should appreciate a qualitative explanation if this is possible.

The problem of producing insulating materials suitable for high-voltage high-frequency work has received considerable attention during recent years, and it is interesting to note that porcelain is being used throughout the aerial and feeder systems, a material about which I should have had grave suspicions. It is regrettable that we have lagged so much behind certain Continental countries in the production of low-loss ceramic materials, a state of affairs which presumably accounts for the use of this comparatively imperfect material. I should be obliged if the authors could give some information as to the temperature-rise in the body of these insulators; and, where they refer on page 338 to losses in the feeders, if they could state what proportion of the total loss is to be attributed to the insulating supports.

It is unfortunate that the authors were unable to incorporate in the paper a rather fuller statement about the cathode follower system. This is a very important new development, and I hope the authors will find it possible to include in their reply a clarification of the information given on page 345, and particularly of the remark that "with a non-linear load the voltage-swings across the load are still almost linear."

Mr. A. Morris: The Post Office short-wave telephone service presents similar problems to the Post Office engineers, to those encountered by the staff of the B.B.C. in the development of the short-wave broadcasting service; although, as is pointed out in the paper, there are very important differences in the two kinds of service. The telephone service is a point-to-point service, whereas the broadcasting service is one in which the directed beam is much less narrow. Furthermore, broadcasting entails only a single-way service, and the point of importance in connection with that feature is that a 2-way test, as we understand it in the ordinary point-to-point service, is almost impossible.

In regard to the provision of crystals for the frequency control of the transmitters, what do the authors regard as a safe number of crystals per transmitter and per wavelength? Is it necessary to provide a relatively large number of spare crystals, in order to ensure a satisfactory service? What percentage of spares do the authors employ, other than the stand-by crystals which, I suppose, are provided for emergency purposes? Is any special arrangement made for storing the spare crystals? The stand-by crystals are held in ovens, and I presume they are kept at a suitable temperature to ensure immediate use in the event of damage to a working crystal. What are the limits of constancy of temperature control of these ovens?

In the event of a breakdown of the external power supply, can the whole of the normal transmissions be carried out with the stand-by plant, and if so, for how long?

The authors refer to a comparison of the British short-wave broadcast services with the broadcast services of other countries, the results of which are favourable to the former and confirm that the service is a perfectly satisfactory one. The reports of listeners in the various countries receiving the broadcasts are used for the purpose of such comparisons. Doubtless special steps are taken to ensure that the judgment is made upon the basis of an adequate number of authentic reports which have value from a scientific point of view.

I gather that the time required to effect a wave-change is about 4 minutes, and it would be interesting to know how the transmitters at Daventry compare in this respect with a telephone transmitter. Is it as necessary to effect a very rapid wave-change in the broadcasting service as in

the telephone service? In this connection I should like to know how long it takes to change not only the transmitter but also the array connected to it.

Have the authors any information in regard to the life of the high-frequency valves in the last stage of the transmitter?

I should like to ask whether the demountable or the continuously evacuated types of valve have been used in the last stage of the Daventry transmitters. Such valves are used in the Post Office short-wave transmitters.

With regard to maintenance procedure, how many attendants are required for, say, four transmitters which may be on the air at one time?

Finally, is there sufficient experience to date of the way in which these transmitters will stand up to service? In the very early days a short-wave telegraph transmitter was quite a wreck at the end of 6 months, because of the very severe electrical strain to which the whole of such equipment was subjected. I know that the nature and quality of the materials has been much improved in recent years, but the deterioration of such items as condensers and resistances, as well as of other items which go to make up a transmitter, has to be considered.

Mr. G. R. Polgreen: In the past, the B.B.C. have been pioneers in the use of the kilocycle or megacycle notation for expressing frequency, as opposed to the use of the wavelength in metres. The latter has very little practical value nowadays except for certain specialized applications in aerial design, and the fact that the frequency bands for carrier wire telephony and radio-communication overlap considerably is an added argument in favour of the universal adoption of the kilocycle notation. I mention this because the authors use kilocycle units in one part of their paper and wavelength units in other parts.

The frequency chart shown in one of the authors' slides is of great interest in indicating the comparatively small proportion of the high-frequency radio band which is allotted to broadcasting, and this chart would make a useful addition to the paper. Perhaps the authors would comment on why the proportion of these frequencies allotted to long-distance broadcasting is so small. Is this due to economic limitations imposed by the high cost of broadcasting channels, or to the demand for space in the frequency spectrum for purposes other than broadcasting?

Mr. K. M. Pearce: Four minutes appears to me to be rather a long time to keep an audience waiting while the wavelength is changed. I suggest it should be done in no more than 15 sec., otherwise there is a big risk of a serious loss of audience.

On page 346 the authors say "The overall efficiency of the transmitter is increased because a large proportion of the power output of the exciter amplifier is fed into the aerial." The simplified diagram in Fig. 28 shows this quite distinctly. Obviously some power will reach the output circuit; but it has to go through the valve, and thereby losses are incurred. The conventional circuit, on the other hand, does not require such a powerful exciter, and therefore it is surprising to find that the efficiency can be improved by using series excitation. I should like to know how much the efficiency is increased.

Fig. 24 shows four valves operating in parallel. Is there any difficulty in getting those four valves approximately matched? Further, is the manufacture sufficiently consistent to allow the discrepancy to be ignored when one or all are replaced?

Mr. L. L. Preston: On page 347 it is stated that in the Standard Telephones and Cables, Ltd., transmitters the filaments of the main amplifier valves are heated by current fed through stopper circuits. According to Plate 8, however, the same valves are fed by the special filament transformers shown in the bottom left-hand corner. One of the disadvantages of the grid being earthed is that the filaments of the valves have a definite potential above earth at radio frequencies. It is therefore necessary not only to reduce the capacitance between the secondary winding and earth to very low values but also to make special arrangements to protect the insulation of the coils from the radio-frequency field by covering the coils with copper shields. It would be interesting to learn whether the transformers have been replaced by generators since the photograph was taken, and, if so, the reason for the change. Presumably the d.c. generator would be mounted on insulator supports and driven through an insulating shaft, by which the capacitance could be reduced to a minimum. Perhaps the authors would confirm this and state how the two systems compare with regard to overall dimensions and capacitance to earth.

One point worthy of note is the much greater overall efficiency of the Standard transmitters as compared with the other. This is no doubt due, in some part at least, to the fact that transformers can now be produced capable of handling large amounts of audio-frequency power, whilst at the same time maintaining the high standard of performance demanded by the B.B.C. Since transformers of this type and size have not been used before in this country a few details concerning them might be welcome.

The inter-stage transformers shown feeding the grids of the final amplifying valves in Fig. 28 are designed to transmit 6 kW of audio-frequency power at any frequency between 30 and 10 000 cycles per sec. with a loss of not more than 0·5 db. In engineering parlance this means that the voltage regulation at full load at any frequency in the working range is not greater than 6 %. The transformer is oil-insulated, and to outward appearance at least is just an ordinary power transformer of, say, 200 kVA rating. It weighs nearly 1 ton.

The modulation transformer (connected between the final audio-frequency amplifying valves and the final radio-frequency amplifying valves) is considerably larger. Its normal rating is 80 kW of audio-frequency power at any frequency between 30 and 10 000 cycles per sec., and its loss is the same as that of the inter-stage transformer, viz. 0·5 db. Taps are provided on both primary and secondary windings to allow for adjustment on test, and although the d.c. supply to the modulated valves is by-passed through a feed reactor the core is excited by direct current due to the unbalance in the static characteristics of the modulator valves, which cannot always be matched correctly. Apart from the fact that it has no cooling tubes or radiator, this transformer has all the appearance of a 3 000-kVA 22 000-volt single-phase power transformer, and its weight is over 6 tons.

From these figures it might at first be thought that the design is very wasteful of material. This, of course, is not so, as the efficiency of over 95 % at 50 cycles per sec. bears out. This large amount of material is necessary for the following reasons. A student or even an experienced engineer normally considers that the winding of a transformer consists of inductances with a magnitude depending on the size of the transformer. It should be realized that above about 1 000 cycles per sec. most transformers cease to behave as inductances and become capacitances coupled through the leakage reactance. The transformer thus becomes a filter, and if the capacitance is too high the transformer becomes equivalent to a short-circuit on the input valves. It will thus be realized that to keep the performance constant within 0·5 db. this filter circuit must be extremely efficient. If a sufficiently low leakage reactance (i.e. of the order of 0·1 %, against the usual 5 % of a power transformer) and self-capacitance are to be obtained, the power/weight ratio as well as the ratio between iron and copper weights must be very different from that of a power transformer.

[The authors' reply to this discussion will be found below on this page.]

SCOTTISH CENTRE, AT EDINBURGH, 28TH MARCH, 1939

Prof. M. G. Say: Plate 1 does not show quite conclusively whether the spacing between the aerial and reflector curtains corresponds to the actual individual quarter-wavelengths or to an average. Although it would probably not lead to any mechanical simplification, would it have been electrically feasible to have employed an average uniform spacing for all three aerials in the array? In connection with the aerial system, I should like to have a definition of the term " triatic," the " tri " part of which seems to have no obvious significance.

The feeder system is very interesting and quite unexpectedly complex. The distribution frame gives rise to a large number of corners in the feeder lines; some of them are quite sharp. These will produce discontinuities of surge impedance, and I note that matching reactances are used " at appropriate points." It would be of interest to have further details of these reactances and where they are placed. Is their location a matter of experiment or of calculation? To the power engineers present it must seem very strange to put a short line, earthed at one end, across a feeder and call it " an insulator." Although both power and telecommunication engineers use transmission lines having essentially the same electrical features, they speak what amount to different languages about them.

It is a sobering thought, and in these days a common one, that this wonderful equipment, this station with its immense potential effect on our lives, is one of a group of activities which can be so badly misused as to render us sometimes aghast at its possibilities for ill.

Mr. W. J. Cooper: Is there no other profitable source of power for broadcasting than a generator driven by an oil engine? Possibly, however, the vagaries of public electricity supply are such that it cannot be depended upon, or maybe the economies of the Diesel engine have again asserted themselves.

Prof. S. Parker Smith: I should like to ask a question with regard to the regulation of the alternators. The authors say that " no regulator can make the alternator fields respond in time to compensate for the rapid fluctuations of load." What is the rapidity of these fluctuations? In ordinary power work we manage with quick-acting regulators—doubtless the authors' problem is a very special one. The regulation figures are exceedingly close—indeed rather worse for the designer than anything in pre-regulator days. In those days the only way of giving an honest guarantee was to put in an enormous machine and underload it. Does the authors' machine get hot? If so, what has the designer discovered to get 2·5 % regulation at unity power factor and 12·5 % regulation at 0·85 lagging power factor?

THE AUTHORS' REPLY TO THE DISCUSSIONS AT LONDON, MANCHESTER, AND EDINBURGH

Messrs. L. W. Hayes and **B. N. MacLarty** (*in reply*):

London.

Col. Angwin questions the usefulness of the power-distribution diagrams given in the paper. In our view the advantage of this type of diagram is that it gives a practically complete specification of the radiation from a directional aerial. From such a diagram the standard type of diagram favoured by Col. Angwin can be constructed for any angle in the vertical or horizontal plane. This standard type of diagram was used in the earlier days of Empire broadcasting; but since any one horizontal polar diagram holds only for a given vertical angle, and any one vertical polar diagram holds only for a given horizontal angle, a large number of this standard type of diagram are required to give the same information as is contained in the power distribution diagrams given in the paper.

The aerials which are slewable at Daventry are as indicated at the bottom of page 326 and in Table 3, the width of these aerials also being shown in Table 3 and in Fig. 13. We agree with Mr. Smale's statement regarding the slewing of aerials, and we feel that the difficulty of slewing the direction of the diagram without distorting it is greater when the aerial contains but few elements.

Both Col. Angwin and Mr. Wood raise the question of re-broadcasting transmissions from Daventry, a point also mentioned by Mr. Gracie. There is no doubt that, so far as the general listener is concerned, better results can be obtained by taking advantage of the much more highly developed receiver and receiving aerial system, which would generally be available when the Daventry transmissions are re-broadcast through local broadcasting stations, but which he could not provide himself. It must be remembered, however, that it is necessary to cover very much wider areas with the Empire transmissions than are covered by a point-to-point service or by a local broadcasting service, and, to ensure such

coverage, that a large number of re-broadcasts, involving the use of a relatively large number of point-to-point transmissions would be necessary. It is not always convenient for local broadcasting stations or national broadcasting networks to relay programmes from the Empire Station, owing to local-programme commitments; and on the frequent occasions when direct reception by the listener is good, an alternative programme is provided by such reception from Daventry.

It is, furthermore, necessary to cater for the direct listener, particularly in those parts of the Empire where such a listener is not within the range of a local broadcasting service. It is for this reason that it has not been possible, up to the present, to envisage the use of a transmitting technique (such as single sideband) which would prevent the ordinary listener with his own receiver from hearing the Daventry transmissions. This does not mean that the broadcaster would not like to be able to take advantage of the undoubted benefits which would result from single-sideband transmissions (the possibility of carrying out a specific experiment is, in fact, under review); but while the extension of re-broadcasting and the possible use of single-sideband transmission may ultimately help to improve the quality of the signal available to the listener, it does not remove the necessity for an adequate number of channels on which to transmit. The number of frequencies registered for use by Daventry (19) is almost insignificant when compared with the number of frequencies notified for use by some of the important point-to-point transmitters, such as Rugby (51), Rocky Point (52), Kootwijk (86), Paris (108), and Moscow (268).

We think that Mr. Wood has misunderstood our remarks regarding the use of concentric feeders. His statement that the use of this type of feeder has been given up is perhaps misleading. Concentric feeders have never been used extensively at the Empire Station except in connection with aerial experiments which particularly required them.

The balanced open-wire type of feeder was used at the Empire Station because it is very much cheaper to construct and is easier to repair than any other type; further, as stated in the paper, it is particularly suitable for feeding aerials of the horizontal dipole type. Another consideration which influenced the decision was the possibility that considerable modifications to the original layout of the aerial system might become necessary. The open-wire feeder possesses an advantage in this respect.

It is noted with interest that Mr. Wood has not experienced flashover trouble with concentric feeders. We presume that, in his experience, they have been used in conjunction with aerials which are not fitted with switchgear for the purpose of reversing or slewing the beam, in which case the danger of flashover due to the application of power to a feeder which is incorrectly terminated is greatly reduced.

With regard to Mr. Wood's question whether modulation of one transmitter by another has been experienced, we are glad to state that no difficulty has been encountered in this direction. Ample spacing between feeders and careful balancing appear to have prevented this trouble. The only instance of such interaction was due to coupling between aerial arrays and not between feeders.

The switching system for concentric feeders described by Mr. Wells was considered when the Empire Station was designed, and we agree that there is no doubt of its convenience and reliability; but the particular example cited by Mr. Wells was not designed for use with feeders of 5 in. diameter. We feel that the cost of this type of switching frame designed for large feeders would be at least as high as that of the open-air switching station, and such a frame would be liable to severe damage in the event of internal flashover. We suggest that it is not possible to carry out repairs on one section of this type of frame without making the whole frame dead.

After nearly 3 years' experience with the open-wire system at Daventry, we are convinced that the choice was the correct one for this particular station, but we wish to emphasize the statement made in the paper that the concentric feeder has advantages and is preferred in cases where the runs are short, the aerials require an unbalanced feed, and the feeder is not liable to be mismatched.

In reply to Mr. Gill, the insulators used to support the original aerials and feeder lines were of porcelain, but other materials having a lower loss are now being used for new construction.

With reference to the remarks of Messrs. Wood and Bishop on the subject of synchronization of transmitters, this practice is adopted regularly at Daventry and as many as three transmitters have been regularly used to serve different directions with the same programme on the same frequency. As stated in the paper, provision is made in the drive room for driving any four transmitters on a single frequency.

Mr. Bishop raises a most important point on the question of electrical interference. On the short waves the electrical interference caused by the ignition systems of motor-cars is undoubtedly serious, and the prevalence of this interference may well reduce the short-wave listening audience below what it might be. The effective suppression of this interference would be a step which would greatly ease the problem of reception on short waves.

We should like to thank Mr. Sandeman for his contribution to the discussion, which extends the utility of the power-distribution diagrams.

We also desire to thank Col. Angwin for drawing our attention to an ambiguity in the description of the series amplifier circuit. It should have been made clear that there is no direct transfer of radio-frequency energy from grid to anode circuits by the medium of electrostatic coupling between the grid and anode of the main valves.

With regard to Mr. Grant's remarks on the relative efficiencies of the series and balanced amplifiers, in which he proves that there is no difference in the overall efficiency of the two systems, we agree that this would be so were it not for the fact that, in order to ensure stability of the balanced amplifier, it is usually necessary to connect a damping resistance between the grid and cathode of the output stage. The greater part of the output power of the penultimate amplifier is dissipated in this resistance. In the case of the series amplifier, damping of the grid input circuit is automatically pro-

vided by the reversed feedback which exists. A damping resistance is therefore not required and a proportion of the output of the penultimate amplifier is available to be fed into the aerial. Mr. Grant's argument, therefore, becomes invalid if this practical point be taken into consideration.

We are of the opinion that Mr. Grant has perhaps attached too much importance to the greater overall efficiency of the series amplifier. When the overall efficiencies of the two types of transmitter described in the paper are compared, two facts must be borne in mind. First, that the higher efficiency of the Standard Telephones and Cables transmitters is due basically to the use of modulators operating in the Class-B condition. Secondly, the efficiency figures quoted are the ratio of output to input from the supply mains. The differences in efficiencies of main and auxiliary converting plant and the differences in filament consumption, etc., must be taken into account. This is proved by an examination of the overall efficiencies of the two Marconi Class-B transmitters which were put into service a few months ago. The high-frequency circuits of these transmitters are similar to those of the series-modulated Marconi transmitter described in the paper, the efficiency figures being as follows for an unmodulated carrier power of 100 kW:—

Efficiency from supply mains to feeder output:

Zero modulation ..	.. 31·2 %
30 % modulation ..	.. 31·1 %
100 % modulation ..	.. 34·6 %

The filament emission and anode dissipation of the main output valves in these transmitters permit an unmodulated carrier output at 32 metres of 120 kW, and, under these conditions of operation, the efficiency is equal to that obtained from the Standard Telephones and Cables transmitters.

The following figures answer Mr. Grant's question regarding the performance of the Marconi Class-B transmitters with and without feedback:—

Harmonic distortion.

Tone frequency. 400 *c./sec.* Modulation depth	*R.M.S. distortion content.* Without feedback	With 5db. feedback
50 %	1·55 %	0·9 %
80 %	3·4 %	2·6 %

Noise: 65 db. below 90 % modulation.

Prof. Willis Jackson suggests that we should give further information regarding the cathode follower system. While agreeing that it is a most important subject, we regret that it is impossible in the space at our disposal to comply with Prof. Willis Jackson's request, neither can we clarify the remark that "with a non-linear load the voltage-swings across the load are almost linear." We can, however, give an assurance that this is the case and that it is one of the valuable characteristics of the cathode follower, the advantages of which have recently been described in the paper on "The Marconi–E.M.I. Television System" by Messrs. Blumlein, Browne, Davis, and Green.*

* *Journal I.E.E.*, 1938, vol. 83, p. 758.

We are able to confirm Mr. Green's statement that the CAT. 14 S.W. valve has been trouble-free, but we feel that we should point out that high-power valves of other makes have also been equally free from trouble.

Mr. Green points out that the Marconi series-modulated transmitter was designed for use with floating carrier. This system has been tested out since the paper was written and has been found to be satisfactory, and it gives a power saving approximately equal to the figures quoted by Mr. Green. In answering Mr. Grant's question we have already dealt with Mr. Green's query on the relative efficiencies of the series and balanced amplifiers.

Mr. Gracie compares the relative efficiencies of the two types of transmitters and asks whether there are any other factors such as saving in capital cost which justify the use of a transmitter that is more extravagant in power consumption. At the time when the original Empire transmitters were ordered, no high-power Class-B transmitters were in operation in this country and only a few in America. There was some doubt in everybody's minds whether the system would be entirely successful from the point of view both of freedom from distortion and of reliability. It was decided, therefore, to install at least one transmitter of the conventional type.

It is not possible to answer Mr. Gracie's question regarding the number of people who regularly listen on short waves. It is, however, certain that the potential audience is very large, for the majority of commercial broadcast receivers manufactured and sold in the last few years contain provision for the reception of the short-wave bands. In any case, the size of the audience is not necessarily the truest criterion of the importance of providing a service.

In answer to Mr. Wells's point regarding the height of the vertical and horizontal aerials, the experimental aerials were supported on the same triatic and the same overall height was therefore available for both types of aerial. We believe that the vertical aerials used for test purposes were, in the opinion of their designers, of the optimum height for the purpose. Both Mr. Kirke (in the London discussion) and Prof. Willis Jackson (at Manchester) refer to the observed superiority of horizontal over vertical polarization. We share Prof. Willis Jackson's surprise at the results obtained, but we hesitate to put forward an explanation. Perhaps the one suggested by Mr. Kirke may commend itself to him.

Manchester.

Mr. Jones states that he does not understand the method whereby the turntable permits the use of spare valves. Study of Fig. 29 in the paper should make this clear. Taking the modulated amplifier unit as an example, it will be observed that there is a set of valves mounted at the front of the turntable and a set of valves at the back. Either of these valves can be brought into use by the operation of connecting switches. In the event of one pair of valves becoming defective, then the switch is opened and the turntable rotated through 180°, which brings the appropriate circuit opposite to the spare valves. The connecting switch associated with these valves is then closed and the spare valves rendered operative.

In reply to Mr. Jones's question regarding the B.B.C.'s preference for high-power modulation, it can be stated definitely that this is based on experience. The low-power modulation system, when used on short waves, is not easy to adjust with rapidity. This is, of course, owing to the relatively large number of high-frequency circuits which are subject to modulation. In the case of transmitters using high-power modulation, the modulation is applied to the anodes of the final and, in some cases, the penultimate amplifiers, and the adjustment of the high-frequency circuits of these amplifiers is not very critical. In our opinion the difficulty of adjustment of a number of high-frequency circuits arises in any form of high-frequency amplifier, whether it be of the orthodox type or one of the modern high-efficiency type.

We are in agreement with Prof. Willis Jackson's comments on the suitability of porcelain as an insulating material at very high frequencies. It should be mentioned, however, that very little trouble due either to excessive loss or to breakage has been experienced with the type of insulator used at the Empire Station, because insulators were designed in such a manner as to reduce the stress in the dielectric to a very low value. It is to be regretted, nevertheless, that difficulties in connection with delivery prevented the use of low-loss insulating materials when the original aerials were constructed. The temperature-rise of the porcelain on the $16\frac{1}{2}$ in. insulators illustrated in Fig. 12 is 5 degrees C. at a pressure of 7 500 volts (r.m.s.) at $13 \cdot 3$ metres. This is the working voltage for 100-kW unmodulated carrier.

Mr. Morris asks whether stand-by crystals are provided. At the Empire Station two crystals are provided for each frequency and are mounted in ovens which hold them at the correct temperature. A switch is provided in order that the spare crystal may be brought into use without delay.

The thermostats hold the crystal to a constancy of temperature control of $0 \cdot 02$ degree C. at an ambient temperature of 18° C.

Information regarding the life of the high-frequency valves in the last stages of the transmitter at Daventry has been obtained, but, owing to the different manner in which valves of the same type are used in different stages of the same transmitter, it would occupy far too much space to attempt to reply to this question. It can be stated, however, that all the high-power valves supplied by various manufacturers at Daventry have had lives considerably in excess of the guarantees, and that the situation from the point of view of the reliability and life of high-power valves is satisfactory.

We cannot agree with Mr. Morris's suggestion that, even in the early days, a short-wave telegraph transmitter became a wreck at the end of 6 months. This is not borne out by our own experience on the two original transmitters supplied by Messrs. Standard Telephones and Cables in **1932**, which are still in regular operation and in an excellent state, or by the condition of one of the earliest beam transmitters, which was purchased secondhand from Marconi's Wireless Telegraph Co. and used for several years as a braodcast transmitter at Daventry.

While we share with Mr. Polgreen a preference for the use of kilocycles and megacycles for expressing frequency rather than the use of wavelength in metres, both systems of notation were used intentionally in the paper, since one portion of it deals with aerial design, for which the wavelength notation is specially suited, and another portion with wavelength allocation, for which the frequency notation is preferable. The proportion of frequencies allotted to long-distance broadcasting is small because broadcasting is the latest comer in this part of the spectrum. This question is dealt with in the Appendix on page 356 of the paper.

Mr. Pearce refers to the efficiency of the inverted amplifier as compared with the conventional circuit. We think that this point is answered in our reply to Mr. Grant.

No difficulty is experienced in the operation of four valves in parallel. These large valves are manufactured with remarkable consistency, and only minor adjustments are necessary when a valve is replaced.

In reply to Mr. Preston, we regret that Plate 8 is a little out of date and shows the filament transformers which were used as an experiment during tests on these transmitters and which have now been removed. All valves are now heated by direct-current generators, the armatures of which are isolated from the insulated filament circuits by means of quarter-wave lines. With this arrangement the armatures of the filament-heating generators may be operated at earth potential so far as the radio-frequency component is concerned.

We also regret that we were prevented from giving further information on the inter-stage transformers. We thank Mr. Preston for amplifying the information on this important point.

Edinburgh.

Prof. Say points out that Plate 1 does not show conclusively whether the spacing between the aerial and reflector curtains corresponds to the actual individual quarter-wavelengths. The spacing between the driver and reflector curtains in every array is fixed at one quarter-wavelength, which is, of course, not apparent from the photograph. It would not be feasible to have employed an average uniform spacing for all three aerials in the array, each of which operates at a different wavelength.

Referring to Prof. Say's question as to the origin of the term "triatic," we think that this is a term used to designate the stay coupling the tops of the masts of a 3-masted ship. The term is extensively used by wireless engineers in this country, and we suggest that it may have been originated by the late Marchese Marconi's mast erectors, many of whom were seafaring men. It has probably been forgotten that the masts used in Marconi's earlier experiments were ships' wooden masts.

The same speaker asks whether the position of the matching reactances at various points in the feeder lines is determined by calculation or by experiment. The position is actually determined by direct measurement of the reflection existing on the lines, and is checked by ensuring that no reflection exists after the matching has been effected.

Mr. Cooper asks whether there is no other profitable source of power for broadcasting than a generator driven

by an oil engine. We think that he has overlooked the fact that the power supply at the Empire Station is derived mainly from the mains of the Northampton Electric Light and Power Co. and that the Diesel engines are used for stand-by purposes. It is of interest to note, however, that the British Broadcasting Corporation, which is one of the largest users of Diesel engines for power generation in this country, has found that the overall cost per unit by Diesel generation is comparable with, and in some cases cheaper than, a mains supply.

In reply to Prof. Parker Smith's question regarding the regulation of the alternators, it must be remembered that, while the regulator may be rapid in response, the maximum delay is in the response of the alternator field. This figure is given on page 352 of the paper as 0·6 sec. for the time to increase the alternator voltage from 100 % to 110 %. This is a relatively long time, having regard to the fact that the transmitter may demand an additional 100 kW of power in 0·01 sec.

Distortion will occur if the voltage at the valve anodes is permitted momentarily to fall by more than 6 %. This condition indicates that the combined performance of the regulator and an alternator having ordinary commercial regulation is not suitable for the particular purpose. It was decided, therefore, to use alternators having an inherent regulation better than that obtained from ordinary commercial machines.

Prof. Parker Smith is correct in his assumption that the result has been achieved not by any new discovery, but by using alternators which are massive for their output. From the commercial point of view this is not an economical proceeding, but, having regard to the relatively small size of the alternators, the extra cost was not serious when expressed as a percentage of the total cost of the station.

THE METADYNE, AND ITS APPLICATION TO ELECTRIC TRACTION

By G. H. FLETCHER, Member, and A. TUSTIN, M.Sc., Associate Member.*

(*Paper first received* 10*th August, and in revised form* 26*th November*, 1938; *read before* THE INSTITUTION 23*rd February, before the* NORTH-EASTERN CENTRE 27*th February, before the* TEES-SIDE SUB-CENTRE 1*st March, and before the* NORTH-WESTERN CENTRE 28*th March*, 1939.)

SUMMARY

The term "Metadyne" is defined as including various forms of dynamo having additional brush-arms intermediate between the usual brush-arms.

The first section of the paper explains the special properties of such machines, especially as sources and users of constant current, or in obtaining special relationships between the current supplied to a load and the voltage across it. The equations for the calculation of the currents and fluxes of such machines are given, and the functions of various stator windings are explained.

The second section of the paper deals with some of the most important applications of the metadyne to traction problems. A number of equipments which have been installed are described in some detail, and schematic diagrams of connections for these equipments are given.

OUTLINE OF THE THEORY OF THE METADYNE

General

The "Metadyne" was invented and developed in a number of forms by Prof. J. M. Pestarini, now of Turin University. The term covers various forms of dynamo in which extra sets of brush arms are placed between those that would be present in an ordinary dynamo. To avoid bad commutation at these additional brushes the main poles are subdivided, and additional interpoles may be fitted in the spaces so provided. Owing to the number of polar projections being increased in this way, and therefore not being the same as the number of poles of the armature winding, it is convenient in order to avoid confusion to speak of "cycles" instead of "pairs of poles." A one-cycle machine has an armature with one pair of poles, a two-cycle machine has two pairs of poles, and so on, whatever the number of polar projections on the stator, the term "cycle" referring to each of the repetitions of identical electrical parts around the periphery.

Metadynes derive their special properties from the fact that the armature reaction plays an essential part in the operation of the machine, and in most cases the m.m.f.'s of the armature provide the principal excitations.

In explaining the operation of metadynes we shall make use of the conventional way of representing current passing through an armature that is shown in Fig. 1, which represents a one-cycle machine, or one cycle of a multi-cycle machine. The axis of commutation is AC, and the current I_1 is shown as entering the armature at A and leaving it at C. This is, of course, purely conventional, and the actual position of the brushes is displaced from these points by an amount depending on the pitch of the end windings. The current in the armature conductors sets up a flux through the field system, exciting all the polar projections in the way shown. On our conventional diagrams this flux Φ_1 may be represented by a single arrow in the axis of com-

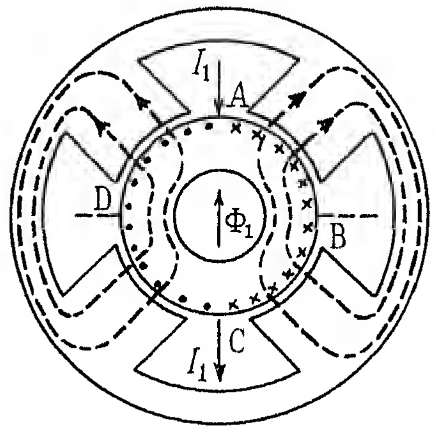

Fig. 1.—Flux due to primary current.

mutation. If the armature is rotating a voltage is induced, owing to the rotation of the armature conductors in flux Φ_1, which is distributed round the armature and reaches a maximum value between the points B and D. If an additional pair of brush arms is provided, placed between A and C, they will have generated between them some voltage V_2. This voltage is proportional to Φ_1 and therefore, below saturation, is proportional to the primary current I_1, or equal to kI_1 where k is some constant. We shall here consider only the case where

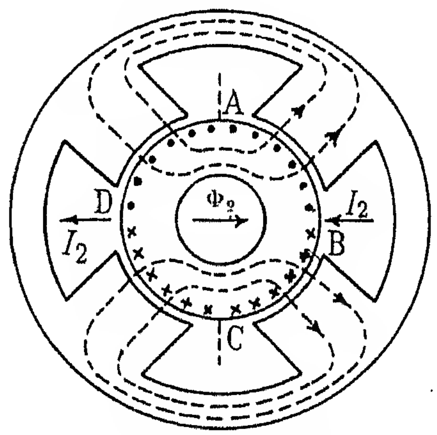

Fig. 2.—Flux due to secondary current.

these additional brush-arms are placed at B and D, where the voltage V_2 is a maximum.

Current which flows through the armature between the secondary brushes B and D, as shown in Fig. 2, sets up flux Φ_2 proportional to the amount of this secondary current in the direction shown by the arrow, and rotation of the armature in this flux produces a

* Metropolitan-Vickers Electrical Co., Ltd.

back e.m.f. between the primary brushes. The amount of this back e.m.f. is kI_2, where k has the same value as before.

Suppose now that the primary brushes are connected to a supply of constant voltage and the secondary brushes are connected to some load circuit; we can immediately see the two basic properties of a metadyne of this type, which are:—

(*a*) Current will flow from the line only until it has built up enough e.m.f. across the load circuit for the back e.m.f. in the primary circuit due to the load current to balance this applied supply voltage. Neglecting resistance drops, this would give $V_1 = kI_2$, and as V_1 is constant this means that I_2 is also constant, so that the load current would be constant, i.e. the output current would not vary with the back e.m.f. of the load.

(*b*) Since the relations $V_1 = kI_2$ and $V_2 = kI_1$ are approximately true, where V_2 is the voltage applied to the load, we have $V_1I_1 = V_2I_2$; that is, the electrical input and the electrical output of such an arrangement would be equal, so that the machine could be kept running with a very small driving torque. The arrangement is, in fact, a transformer converting power at constant voltage to power at constant current.

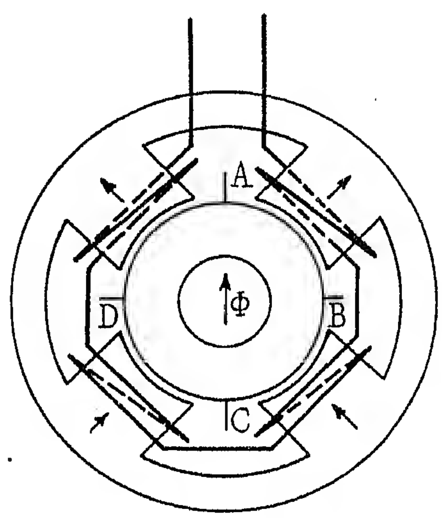

Fig. 3.—A primary variator winding.

Effect of Windings on the Stator

On such a machine, windings may be added on the polar projections of the stator for purposes that will be explained later. The windings on diagonally opposite polar projections will be identical in all cases, and any given distribution of ampere-turns on the two diagonals may be regarded as equivalent to the sum of two component excitations with equal ampere-turns on all poles—one like that shown in Fig. 3, called a primary variator excitation, and the other like that shown in Fig. 4, called a secondary variator excitation. The first gives excitation in the direction of the primary axis and its sign is taken as positive when it assists the primary flux, and the second gives excitation in the direction of the secondary axis and its sign is taken as positive when it assists the secondary flux. Considering the effect of a primary variator, for example, it will be clear that because it gives no excitation in the secondary axis the value of the load current cannot be altered, since it must still rise to the value necessary to excite the back e.m.f. The total flux in the primary axis (Φ_1) must also still correspond with the voltage across the load, and is therefore unchanged. Part of this flux is, however, now provided by the primary variator winding, so that the primary current must be reduced by an amount exactly corresponding with the current through the primary variator. Primary variator excitation thus causes a decrease in the primary current without altering the secondary current or the distribution of voltage. This implies a decrease in input to the machine without a decrease in output, so that retardation would be developed. If this unbalanced torque is supplied by coupling the machine to some source of mechanical power the machine becomes a metadyne generator, and will take power through its shaft and supply a constant current output.

Such metadyne generators have high output coefficients and provide economical and reliable sources of constant current. A supply of power at constant voltage, but of relatively small amount, is required for the primary, and may conveniently be obtained from an exciter.

In a similar way a secondary variator excitation enables us to control the output current of a metadyne,

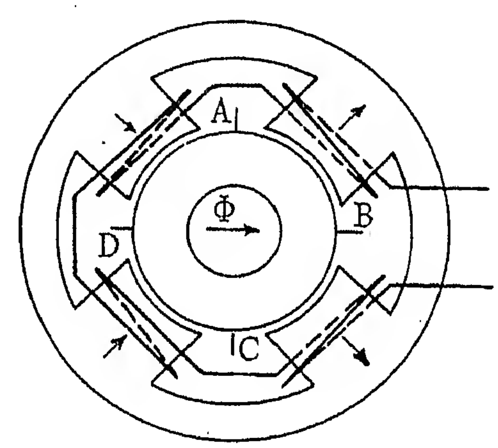

Fig. 4.—A secondary variator winding.

negative variator excitation increasing the output current, either from a metadyne generator or from a metadyne transformer.

Regulator Windings

When the output current is controlled by a secondary variator winding and it is desired to retain the performance of the machine as a transformer, primary variator excitation must be arranged to make the input approximate to the output automatically, so that the driving torque is kept small. This is done by supplying a negative primary variator winding, in this case referred to as a regulator winding, in series with a small shunt-wound "regulator" motor which is coupled to the shaft of the metadyne, as shown in Fig. 5. If the speed tends to decrease even a little, a shunt-wound motor will take a greatly increased current from the line. The passage of this current through the regulator windings on the metadyne increases the power input of the metadyne, preventing further fall in speed. The reverse happens when there is a tendency to rise in speed, so that the arrangement shown in Fig. 5 automatically maintains a balance of input and output on the metadyne transformer without appreciable change in speed.

Stability Windings

In order to limit surges of current resulting from sudden changes in line voltage and in order to prevent any tendency of the currents to oscillate, it is usually necessary to provide stability windings both in the primary and in the secondary circuit. These are series windings in relationship to the respective circuits in which they are connected. It should be noted that a stability winding modifies the characteristic of the machine. For example, a primary stability winding has a similar effect to a secondary variator winding and causes an increase or decrease of the output current proportional to the primary current. The effect is therefore to modify the characteristic by tilting it as shown in Fig. 6. The effect of a secondary stability winding is not to modify the output current but to modify the primary current. It therefore results in a modification of the regulator current only, without change in the output characteristic.

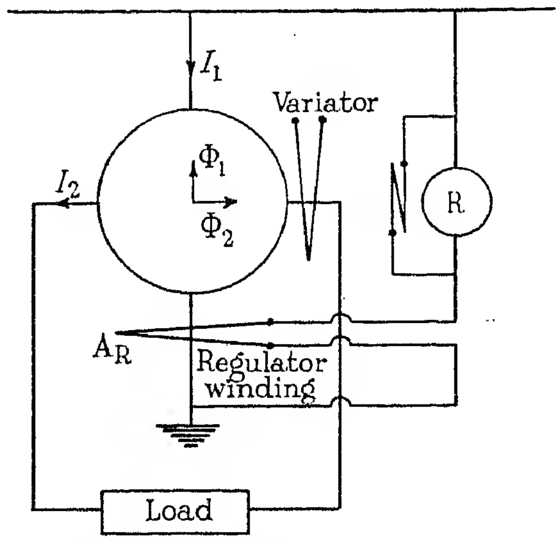

Fig. 5.—Principle of regulator winding to maintain zero torque on a metadyne transformer.

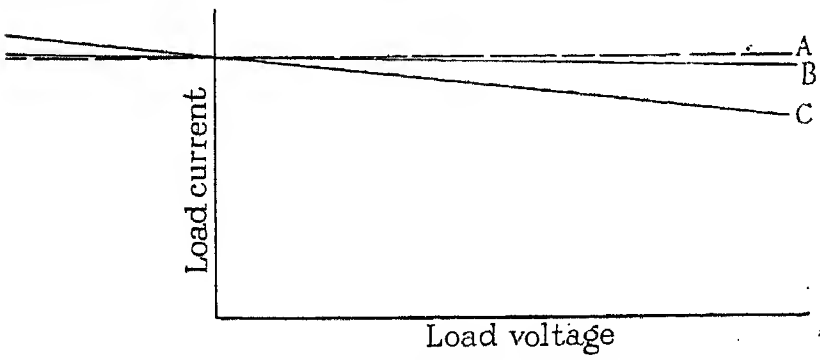

Fig. 6.—Effect of primary stability winding on load characteristic.

A. Theoretical constant-current characteristic.
B. Characteristic as affected by resistance.
C. Characteristic as affected by primary series stability winding.

Use of Variator Windings to obtain Various Desired Characteristics

Since a secondary variator winding provides a means of controlling the output current of a metadyne, any desired relationship of current to voltage on the output side may be obtained by feeding a current to a variator winding which has the desired kind of variation with the change of load. For example, if a variator is directly excited by the voltage across the secondary brushes, it will cause the characteristic of the metadyne to change from a constant-current characteristic to an inclined one, as shown in Fig. 7. If the variator is excited across the brushes BC the characteristic will be as shown in Fig. 8, since the voltage between B and C falls from a value equal to half the line voltage when the load voltage is zero, to zero when the load voltage is equal to the line voltage, and subsequently reverses. More complicated characteristics may be obtained by connecting the variator winding to exciters of special construction excited in various ways.

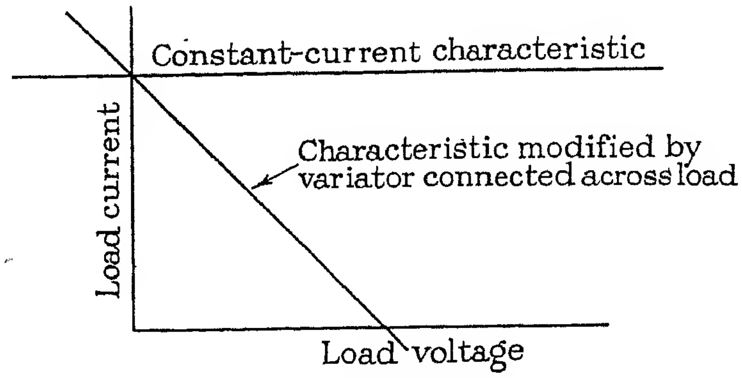

Fig. 7.—Effect on the characteristic of a variator excited across the load.

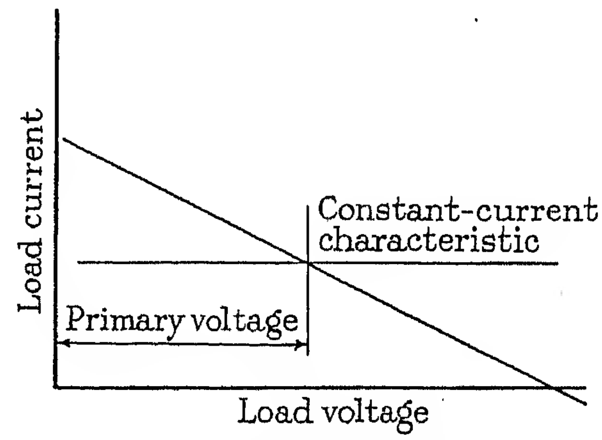

Fig. 8.—Effect on the characteristic of a variator excited across metadyne brushes BC.

Equations for Currents and Fluxes

In practice in the design and calculation of metadynes, the effects of saturation must be taken into account. The most convenient method of calculating the currents and fluxes is to consider the total ampere-turns acting on each of the two diagonally opposite pairs of polar projections. This gives convenient formulae for calculating the output current, taking account of saturation and of the influence of the regulator, variator, and stability windings that may be used in any particular case. The procedure is as follows:—

Referring to Fig. 9, let Φ_{AB} and Φ_{BC} be the fluxes in the two polar projections AB and BC respectively, considered positive when directed out from the armature. The resultant ampere-turns which must exist to produce these fluxes are found by the usual method. Let their values be A_{AB} and A_{BC} respectively. The ampere-turns

due to the armature current I_1 in the armature conductors are $\frac{1}{2}T_aI_1$, where T_a is the number of turns per pole of the armature, since the m.m.f. due to the armature when carrying I_1 increases from zero at point B to T_aI_1 at point A, and has an average value of $\frac{1}{2}T_aI_1$. (Fig. 10

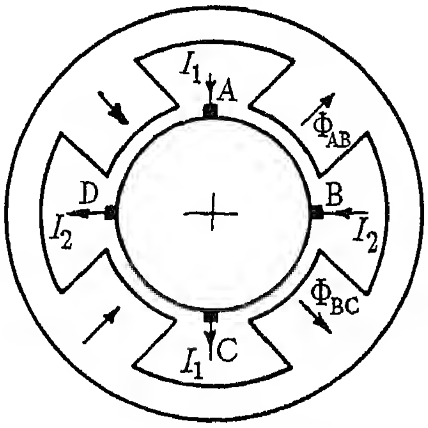

Fig. 9.—Fluxes in stator.

shows the distribution of m.m.f. and flux round the periphery of the armature, and will make this point clear.) Similarly, the m.m.f. on pole AB due to I_2 is $\frac{1}{2}T_aI_2$.

Adding the total m.m.f.'s with proper regard for sign, and including the effect of RI_R regulator ampere-turns, S_1I_1 primary stability ampere-turns, S_2I_2 secondary stability ampere-turns on each polar projection, and W_VI_V secondary variator ampere-turns, gives:—

$$\text{Ampere-turns on AB} = A_{AB} = \tfrac{1}{2}T_aI_1 + \tfrac{1}{2}T_aI_2 + S_1I_1 - S_2I_2 + W_VI_V - RI_R \quad . \quad (1)$$

$$\text{Ampere-turns on BC} = A_{BC} = -\tfrac{1}{2}T_aI_1 + \tfrac{1}{2}T_aI_2 + S_1I_1 + S_2I_2 + W_VI_V + RI_R \quad . \quad (2)$$

$$\text{Adding,} \quad A_{AB} + A_{BC} = T_aI_2 + 2S_1I_1 + 2W_VI_V \quad . \quad (3)$$

$$\text{Subtracting,} \quad A_{AB} - A_{BC} = T_aI_1 - 2S_2I_2 - 2RI_R \quad (4)$$

The value of I_R, of course, adjusts itself to give the condition that the speed is maintained constant, and

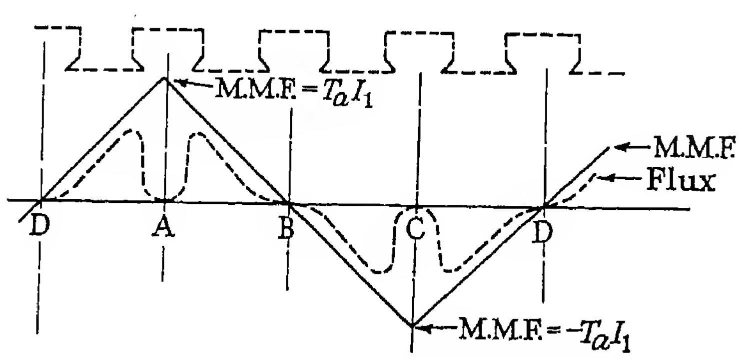

Fig. 10.—Armature m.m.f. and flux due to an armature current I_1.

that the total input is greater than the total output by the total loss in the machine (P_L watts). If V_L is the voltage of the supply, and V_2 the voltage of the load, the input is $V_L(I_1 + I_R)$, and the output is V_2I_2. We thus have the additional relationship:—

$$V_L(I_1 + I_R) - V_2I_2 = P_L \quad . \quad . \quad . \quad (5)$$

If I_V, the variator current, is regarded as given, the values of I_1, I_2, and I_R are determined by solving (3), (4), and (5). The algebraic solution leads to a rather cumbersome expression, but the following relationship makes the physical significance of these equations clear.

We have, from (5),

$$I_1 = \frac{V_2}{V_L}I_2 + \frac{P_L}{V_L} - I_R$$

Inserting this value in (3) gives, writing $P_L/V_L = I_0$, where I_0 is the loss current:—

$$A_{AB} + A_{BC} = T_aI_2 + 2S_1\frac{V_2}{V_L}I_2 + 2S_1(I_0 - I_R) + 2W_VI_V$$

$$I_2 = \frac{(A_{AB} + A_{BC}) - 2S_1(I_0 - I_R) - 2W_VI_V}{T_a + 2\frac{V_2}{V_L}S_1} \quad (6)$$

If there is no primary stability winding, this becomes:—

$$I_2 = \frac{(A_{AB} + A_{BC})}{T_a} - \frac{2W_VI_V}{T_a} \quad . \quad . \quad . \quad (7)$$

The secondary current is therefore equal to the sum of two components. The first is a magnetizing current given by $(A_{AB} + A_{BC})/T_a$. This is constant below

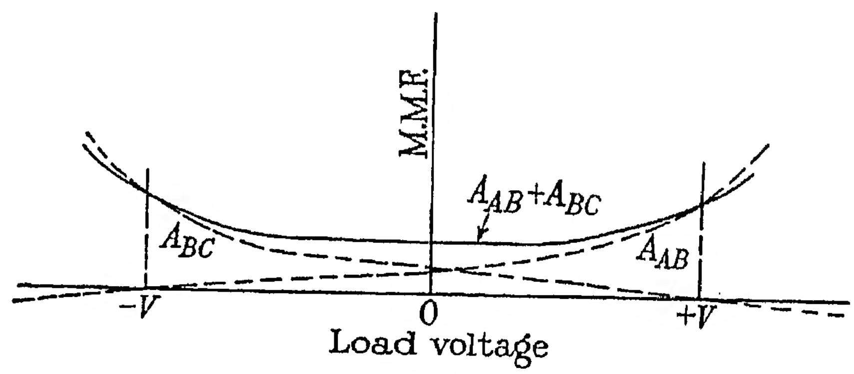

Fig. 11.—Variation of magnetizing ampere-turns with load voltage.

saturation, since the sum of Φ_{AB} and Φ_{BC} is constant given a constant primary voltage. The second component is a current $2W_VI_V/T_a$ proportional to the ampere-turns of the variator winding in the negative direction. When saturation occurs in either pole the magnetizing current is increased, as shown in Fig. 11, so that the effect of saturation is to cause the "constant current" to increase if a certain load voltage is exceeded. The magnetizing component may, however, be relatively small. As the second component is proportional to the variator current, the total output current may be controlled by controlling the variator current.

If a primary stability winding is present we have equation (6) for I_2, instead of equation (7). The extra term $2S_1(I_0 - I_R)$ is very small and may be zero, and the effect of the stability winding is to cause I_2 to decrease as the load voltage increases, as shown by the effect of the term $2(V_2/V_L)S_1$, in the denominator. If this effect is not desired it may, of course, be neutralized by making the excitation of the variator increase suitably in the negative direction, also in dependence upon the load voltage.

Metadynes as Motors

Metadynes of the type described could, of course, be used as motors, fed from a source of constant current. It is more convenient, however, for most purposes, to use

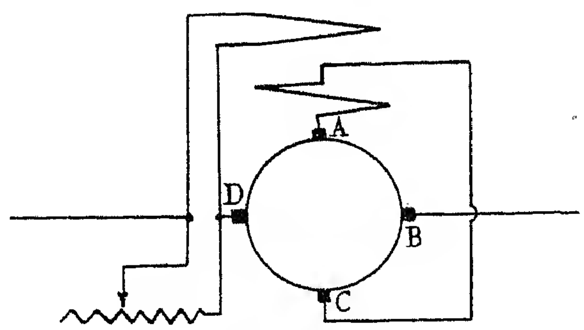

Fig. 12.—Motor for constant-current circuit.

simpler types of motor. One useful arrangement is shown in Fig. 12. The motor is connected in the constant-current circuit, and the field regulated by shunting. Intermediate brush-arms supply a winding

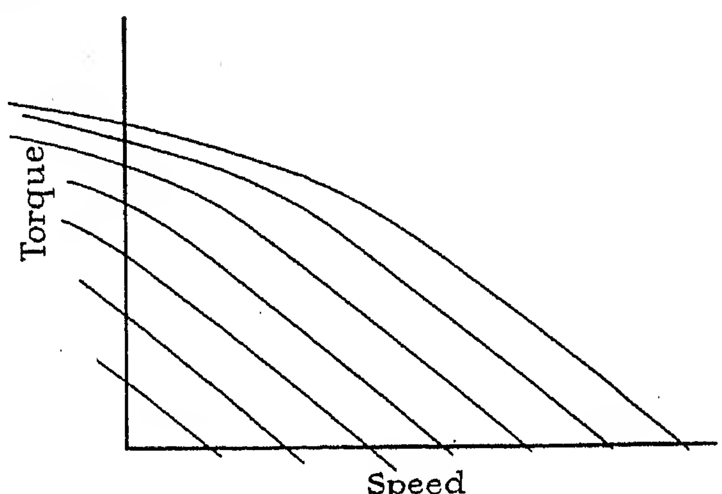

Fig. 13.—Characteristics of motor connected as shown in Fig. 12.

that is connected so as to oppose the main excitation. Such a winding is referred to as a hyper-compensating winding. Since the voltage between the brushes AC

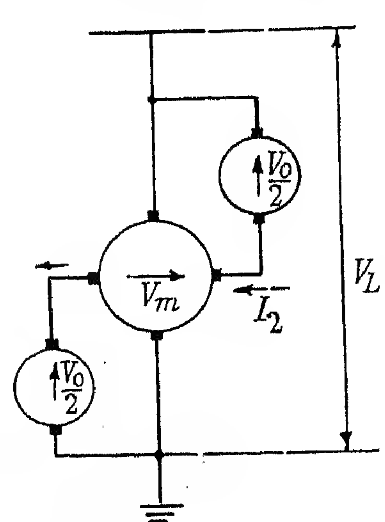

Fig. 14.—The "8" connection, motoring.
$V_0 + V_m = V_L$

is proportional to the speed of the motor, the field and torque fall off with increasing speed. This type of connection gives characteristics such as those shown in Fig. 13. Many other methods of connecting constant-current motors are available, according to the characteristic required.

The "Eight" Connection

When the load supplied from a metadyne may be divided into two equal parts the method of connection shown in Fig. 14 may be used, in which the load is fed

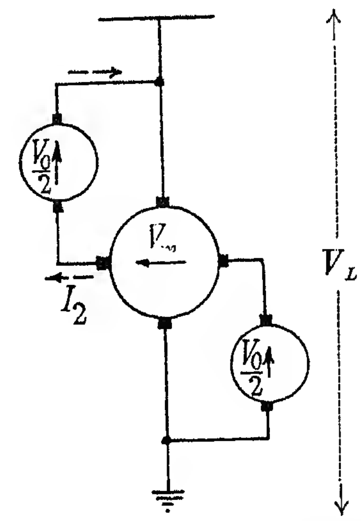

Fig. 15.—The "8" connection, reversed for regeneration.
$V_0 + V_m = V_L$

from the line in series with the metadyne secondary. Change of the total load voltage from zero to a value equal to twice the line voltage can then be obtained with a voltage from the metadyne varying from $+V_L$ to $-V_L$, so that the possibility of voltage control from the metadyne is fully used in both directions. It

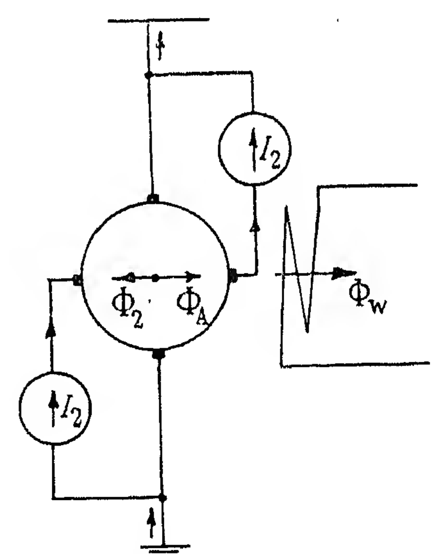

Fig. 16.—Regeneration in the "8" connection by over-excitation of the variator in the direction supplying the back e.m.f.

Φ_W = flux due to variator.
Φ_2 = flux due to armature reaction.
Φ_A = resultant flux supplying back-e.m.f.

follows, of course, that the "eight" connection does not make it economical for the voltage of the load to be reversed for regenerative braking. If this is required it is desirable to reconnect the load for braking as shown in Fig. 15. With this reversed connection the metadyne controls the feeding-back of current to the line just as it controls the flow of current from the line in the circuit of Fig. 14.

An alternative method is to reverse the current of the metadyne by sufficiently increasing the variator excitation in the positive direction, as shown in Fig. 16. This method requires larger variator and regulator coils, and a larger regulator dynamo, so that in practice a change of connections (as shown in Fig. 15) is preferred.

Other Factors affecting Characteristics

In practice, the characteristics are slightly modified by the resistances of the circuit and by the fact that the speed is not constant; but detailed theoretical analysis is not the object of the present paper, and the above brief account of the theory of the metadyne is all that is necessary to enable a number of the most interesting applications of this type of machine to be discussed.

APPLICATIONS OF THE METADYNE

General Field of Application

While it is true that for the majority of applications the parallel or constant-voltage system will give a satisfactory solution, there are many special applications where either constant current or controlled current will give a better solution. By the term "controlled current" is meant either constant current the value of which is controllable by the operator, or a current the value of which has the general characteristics of constant current, such as a limited value on short-circuits, but which varies in a predetermined way with the working condition of the load.

A constant-current system has special advantages where the motor must maintain its torque over a wide range of variation of speed. In such cases it is possible not only to obtain an ideal relationship between torque and speed to suit the particular requirements, but also to reduce the size of motors considerably, and to simplify the control gear.

The speed of a motor supplied from constant voltage can only be reduced by increasing the flux, and this can only be done efficiently if the iron sections are sufficiently great to provide unsaturated paths for the increased flux. In the case of a motor supplied from a variable-voltage source, the speed of the motor may be reduced to any desired amount by reducing the voltage applied to the motor. Where the current passing through the motor field is controlled independently of the motor speed, very fine graduations in torque may be obtained.

Since 1933 a large number of metadyne applications have been tried out, and in the following pages some of these experiments will be described. In a number of cases the experiments were followed by commercial applications which have proved quite successful. The most rapid development has occurred in the field of traction, but the metadyne is capable of providing new solutions for many problems in other fields. Some of these applications have already been developed, and work is in progress on others.

Use for Passenger Transport

The metadyne, in the form either of a "d.c. transformer" or of a mechanically driven generator, owes its usefulness chiefly to the ease with which it enables the current supplied to depend in a predetermined way on the back e.m.f. of the load supplied. In their simplest forms metadyne generators and transformers are sources of constant current. They automatically give just sufficient e.m.f. to overcome the varying back-e.m.f. of the load and maintain the current constant. It is extremely simple, however, to arrange the excitation so that the output current rises and falls as a predetermined function of the back e.m.f. and thus of the speed of the motors supplied, according to the characteristic required. The maximum current is limited, even on short-circuit, and an ideal relationship of torque to speed is obtained according to the particular requirements. In such equipments the motor speed is chiefly controlled by the variation of the voltage applied to the motor terminals. Low motor speeds can therefore be obtained without increase in the flux of the motor, so that where a wide range of speed control is required the motors may be reduced in size. The torque may be maintained or varied smoothly without notching, and in braking the equipments are inherently regenerative down to standstill of the motor.

These features are obviously of the greatest interest in the solution of problems of electric traction, and it is in this field that the metadyne has found one of its first and most important applications. Some of the ways in which the metadyne is being applied in electric traction will now be described.

The system of the London Passenger Transport Board and the electric railways in other large cities must meet certain conditions of operation. High accelerations and high retardations are necessary, particularly where the service requirements are increasing. Multiple-unit operation is also required. As the distance between stations is short the schedule speeds can only be maintained by braking from comparatively high speeds, which means not only the destruction of the kinetic energy stored in the train but also the consumption of large quantities of brake-shoes and tyres. The by-product of this braking in the form of iron dust is in itself a problem, as it finds access to the motors and electrical equipment, and can be responsible for very high maintenance costs.

In the standard equipment the speed is increased by cutting out successive steps of resistance. During this period rheostatic losses of very high order occur, and each notch gives a mechanical impulse to the train. These impulses are particularly noticeable where high rates of acceleration are required, unless the control is complicated by a large increase in the number of notches. In order to bring the train to rest, mechanical brakes are applied.

The application of the metadyne offered the attractive features of eliminating sudden changes in the rate of acceleration, and permitting the motors to convert the kinetic energy into electrical energy during braking, the metadyne transforming the varying voltage of the motors to constant voltage of such a value as to permit the energy to be returned to the line.

Preliminary tests.

Before such an equipment could be installed on a train and put into service, it was necessary to build an experimental metadyne together with control gear, and to test

the equipment by connecting the metadyne so that it would give supply to suitable motors. The motors were mechanically coupled to a large flywheel, which was proportioned in such a way as to represent the mass of the train. The tests were made with a view to demonstrating the operation of the metadyne under every conceivable condition which might occur in service. These conditions included: (1) Short-circuit of the line while motoring or regenerating; (2) short-circuit of the motors (one or both); (3) sudden increase in the line voltage when motoring or regenerating; (4) interruption

In this equipment a metadyne transformer supplies two traction motors. The "eight" connection is used, and the connection is reversed as between motoring and regenerating (as already explained) by the drum switch (5). This switch does not break current. The motors are separately excited from the exciter by the fields (16). There are also small series windings that are chiefly required to equalize the current between the two motors, as the motors are effectively working in parallel (referring to Fig. 1, the voltages AB and CD on the metadyne commutator are necessarily always equal).

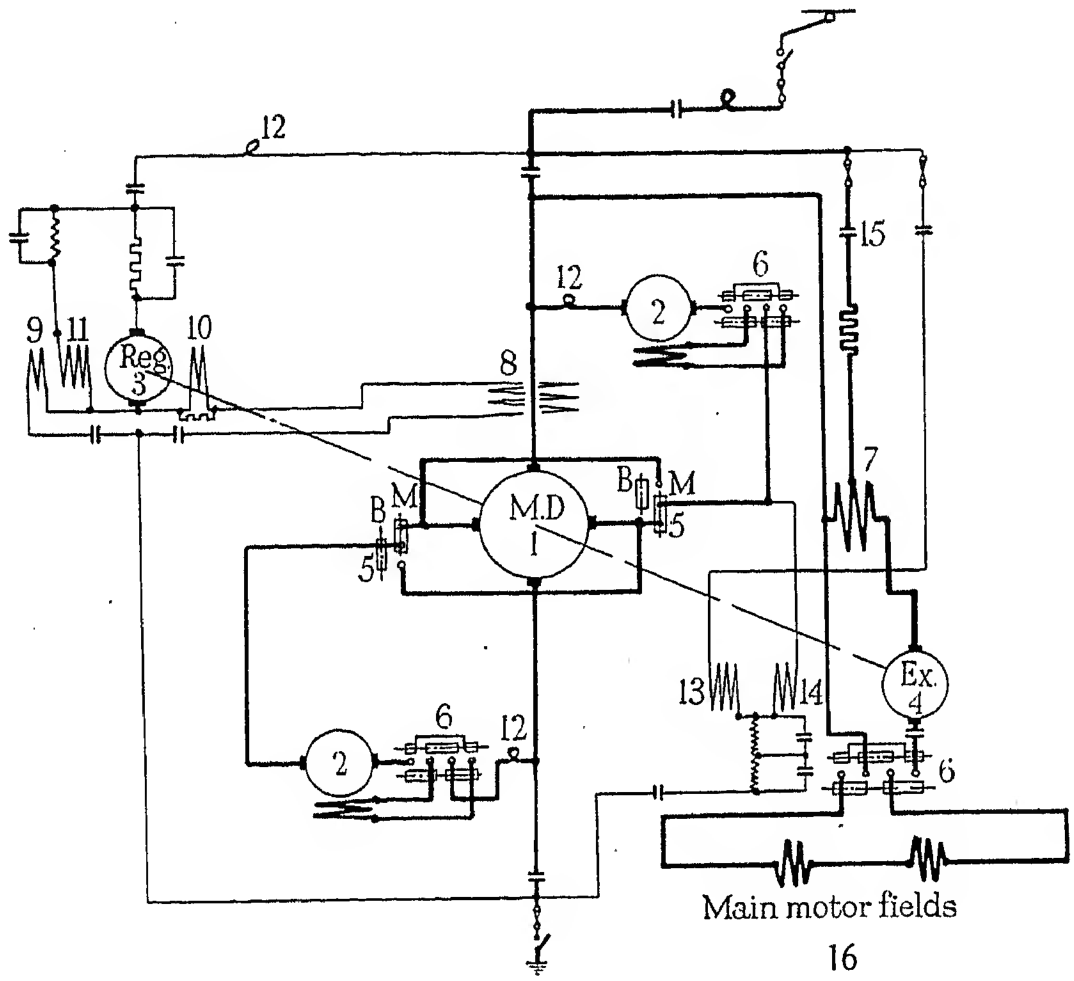

Fig. 17.—Diagram of connections of first experimental equipment using metadyne Type MD50D.

1. Metadyne.
2. Two motors connected in reversible "8."
3. Regulator dynamo.
4. Exciter for motor fields and variator.
5. Motoring-generating change-over drum switch.
6. Reverser drums for motor series and separately-excited fields.
7. Variator winding, also used as "entry" winding in connecting metadyne to line.
8. Regulator winding on metadyne.
9. Series field on regulator dynamo, operating only during starting and coasting.
10. Reversed series field, operating only when metadyne working.
11. Shunt field of regulator dynamo.
12. Overload protection.
13. Exciter winding supplied from line.
14. Exciter winding supplied from difference between line voltage and motor voltage.
15. Contactor to close "entry" circuit through variator.
16. Traction-motor separately-excited fields.

of supply followed by remake; (5) interruption of the line circuit during regeneration; (6) open-circuit of one of the two motors.

As a result of these tests it was found that, with minor modifications to the metadyne which had been built, all possible service contingencies could be met. A 2-coach train was then equipped on the underground railways of the London Passenger Transport Board, and was put into experimental service. The schematic diagram of the first experimental train is shown in Fig. 17. The results obtained in service were satisfactory, but as the train consisted of only one unit the amount of running was limited. Moreover, no experience could be obtained with multiple-unit operation.

The connections of the regulator dynamo follow the principles already explained, the machine being essentially a shunt-wound dynamo connected in series with the "regulator winding" (8) on the metadyne, and so maintaining the speed within certain limits of variation. When the regulator winding is in series with the regulator dynamo, the high inductance of the former makes the circuit secure against sudden changes of line voltage or short-circuits, and to counteract the rather considerable resistance of the regulator circuit a reversed series winding, shunted by ohmic resistance, is also provided on the regulator dynamo.

The regulator dynamo is also used to run the metadyne up to speed, and to keep it running when the train

is standing and coasting. During such periods the regulator winding is disconnected, and to make the machine capable of giving the desired high starting torque, and to protect it from risk of flashing due to short-circuits, and so on, a series winding (9) is brought into the circuit for these conditions.

The metadyne is disconnected from the line during standing and coasting, and since it is not desirable to connect it direct to the line without back e.m.f., the connection is made in two steps. The first step connects it through a small resistance and a part of the "variator winding" (7), which builds up back e.m.f. between the metadyne brushes; so that the second step, which completes the normal connections, may be made without appreciable surge of current or sparking at the brushes.

The exciter supplies both the variator field of the metadyne and the separate excitation of the traction motors. These are connected in series, so that to a large extent the fields of the traction motors are strengthened or weakened at the same time as the motor armature current is increased or decreased under control of the variator. This has the desirable result that the ratio of field strength to armature current of the traction motors does not vary very much over the whole range of operation.

The special characteristic of the exciter, which determines the variation of the torque of the traction motors as a function of speed, was obtained by the use of two exciting windings, one supplied from the line and the other from the difference between the line voltage and the motor voltage. The exciter was saturated. This arrangement results in a smooth reduction of the exciter voltage after a certain motor voltage is exceeded. In later equipments this arrangement was superseded by one with further refinements.

Experimental 6-car train, and later equipments.

The London Passenger Transport Board were sufficiently convinced of the possibilities of the scheme to place an order for a train of three 2-coach units, and these equipments were built and put into service. Fig. 18 illustrates the metadyne unit, and the diagram of connections is shown in Fig. 19. This equipment differed from the first experimental equipment in that each metadyne controlled four motors connected in parallel. The reason why the parallel connection was used rather than the series connection was partly to avoid increasing the current per motor and partly because the conditions are rather more desirable should one of the four motored axles experience wheel-slip.

On this equipment the exciter was a wave-wound machine, with two pairs of adjacent poles excited respectively from the motor voltage and the difference between the line voltage and the motor voltage. This arrangement gives a moderate torque when starting, which increases smoothly and rapidly to a maximum, and again decreases as high speeds are attained.

The circuit for "entry" or connection of the metadyne to the line was improved, in that the excitation was applied on one pair of diagonally opposite poles in entry for motoring, and on the other pair in entry for regeneration, according to the quadrant of the metadyne across

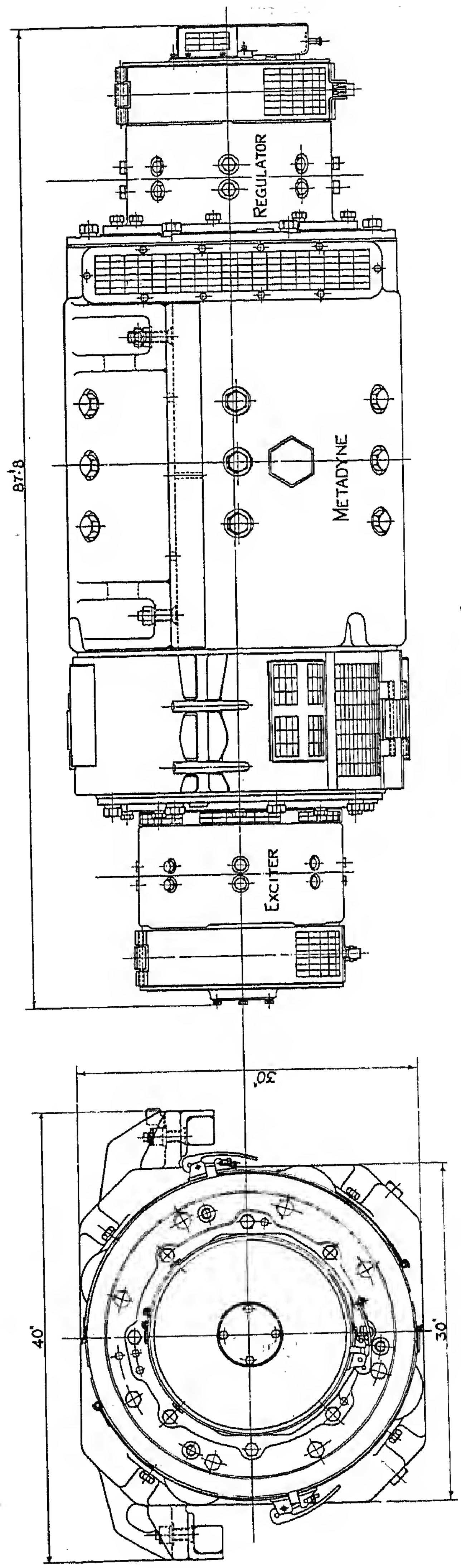

Fig. 18.—Outline drawing of MD52 metadyne.

which the motors are connected. On all other points the equipments were generally similar to the first experimental equipment.

Tests on this train showed that the performance obtained was in accordance with calculations; the rate of acceleration was high, the acceleration was smooth, and the equipment was reliable. The regenerated energy amounted to about 25 % to 30 % of the motoring energy when measured at the train. A chart record of a typical run is shown in Fig. 20. This record was made during a run in rush-hour service, using the regenerative brake only down to a speed of about 5 m.p.h., at which point the air brake automatically takes over to make the final stop. The notched appearance of this chart is due to the type of recorder used. The variations of current are actually perfectly smooth.

In view of these results the London Passenger Transport Board placed an order for 58 equipments, substantially all of which are now in constant service. Fig. 21 illustrates the latest metadyne unit, and Fig. 22 shows the diagram of connections. The mechanical arrangement is modified in that the exciter and the regulator dynamo, instead of being overhung at the ends of the main machine, are made as a separate 2-bearing set, coupled to the armature of the metadyne through a flexible coupling. The frames of the metadyne and of this auxiliary set are rigidly connected together, and supported through rubber blocks under the coach frame, as a single unit.

Certain modifications have been made in the connections as compared with the first and second experimental equipments, the chief being that the manner of producing the back e.m.f. in the metadyne before connecting to the line has been improved still further, the part of the winding used for entry in regeneration being shunted to reduce the rate of rise of flux, and so to avoid excessive "transformer" voltage in the commutating coils. In the case of this equipment the service rate of braking of 3 m.p.h. per sec. (average) was too high to permit 100 % of the braking to be obtained on the motored axles without exceeding the limits of adhesion, and it was found necessary to apply air brakes to the non-motored axles at the same time as regeneration was applied to the motored axles. When the regenerated current falls to a predetermined low value during normal braking, or on account of loss of regenerated current due to any other cause, air brakes are automatically applied also to the motored axles. During normal braking approximately two-thirds of the total braking effort is applied through regeneration, and one-third by the air

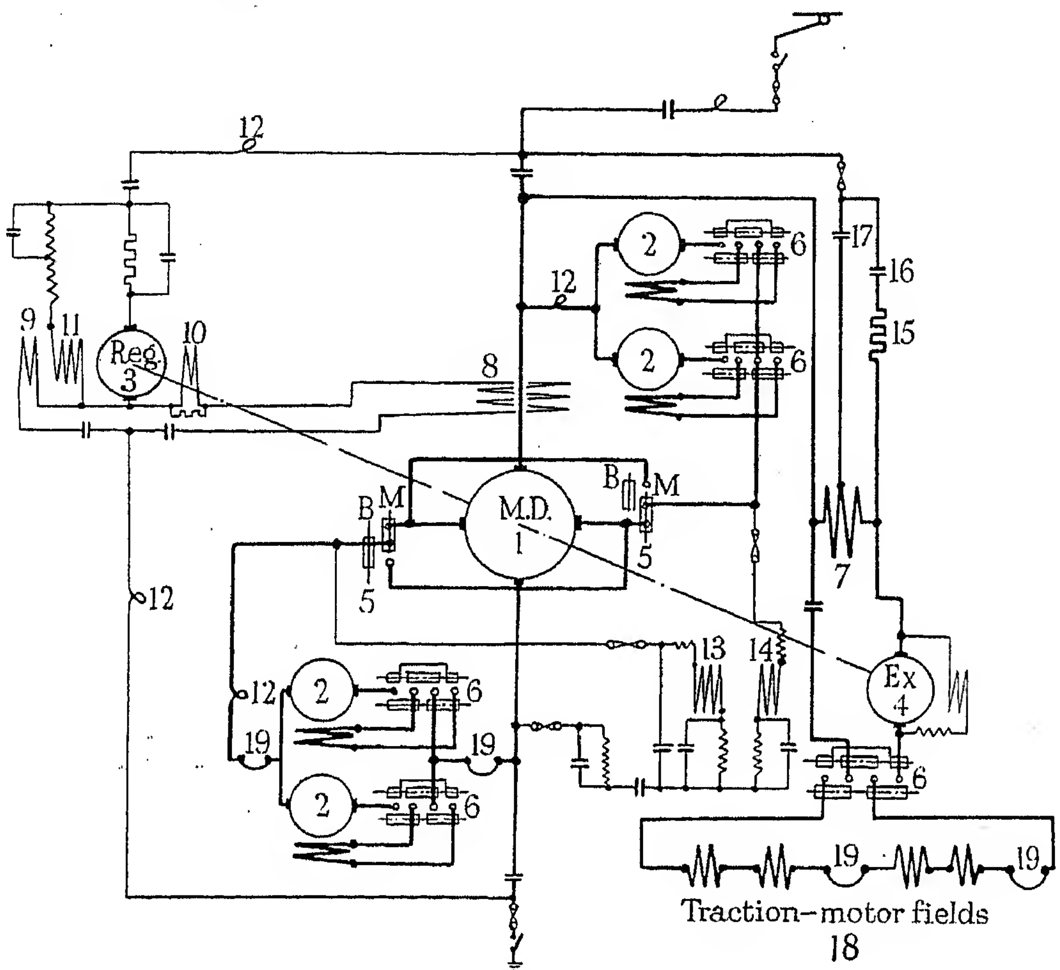

Fig. 19.—Diagram of connections of 2-coach unit for 6-coach experimental train using metadyne Type MD52.

1. Metadyne.
2. Four motors, connected two pairs in parallel in reversible "8."
3. Regulator dynamo.
4. Exciter for motor fields and variator.
5. Motoring-generating change-over drum switch.
6. Reverser drums for motor series and separately excited fields.
7. Variator winding, also used as "entry" winding in connecting metadyne to line.
8. Regulator winding on metadyne.
9. Series field on regulator dynamo, operating only during starting and coasting.
10. Reversed series field, operating only when metadyne working.
11. Shunt field of regulator dynamo.
12. Overload protection.
13. Exciter winding supplied from motor voltage.
14. Exciter winding supplied from difference between line voltage and motor voltage.
15. Resistance used for "entry" for motoring.
16. Contactor used for "entry" for motoring.
17. Contactor used for "entry" for regeneration.
18. Traction-motor separately-excited fields.
19. Couplers between two coaches.

brakes. The effect of this is, of course, to reduce the total regenerated energy which could be obtained without the use of air brakes, and under these conditions the return of energy to the line is approximately 15 % of the energy taken during motoring, when measured at the train.

One of the difficulties experienced with these equipments has been due to the question of the receptivity of the line for regenerated current. It will be realized that conditions occur when the regenerated current in a section exceeds the power requirements from the line, and as the d.c. supply is provided in some sections by mercury-arc rectifier substations, reverse current cannot pass through the substation and must be absorbed in some other way. A device often used in such a case is to install at each substation an artificial load of resistances with either an over-voltage relay or a reverse-current relay, which automatically connects them in circuit when required to absorb the regenerated load. As this was not found possible in this instance it was necessary to install on each unit a resistance which would take the regenerated load for a short period. It will be realized that it is only in exceptional circumstances that this resistance is required, as normally the line is receptive.

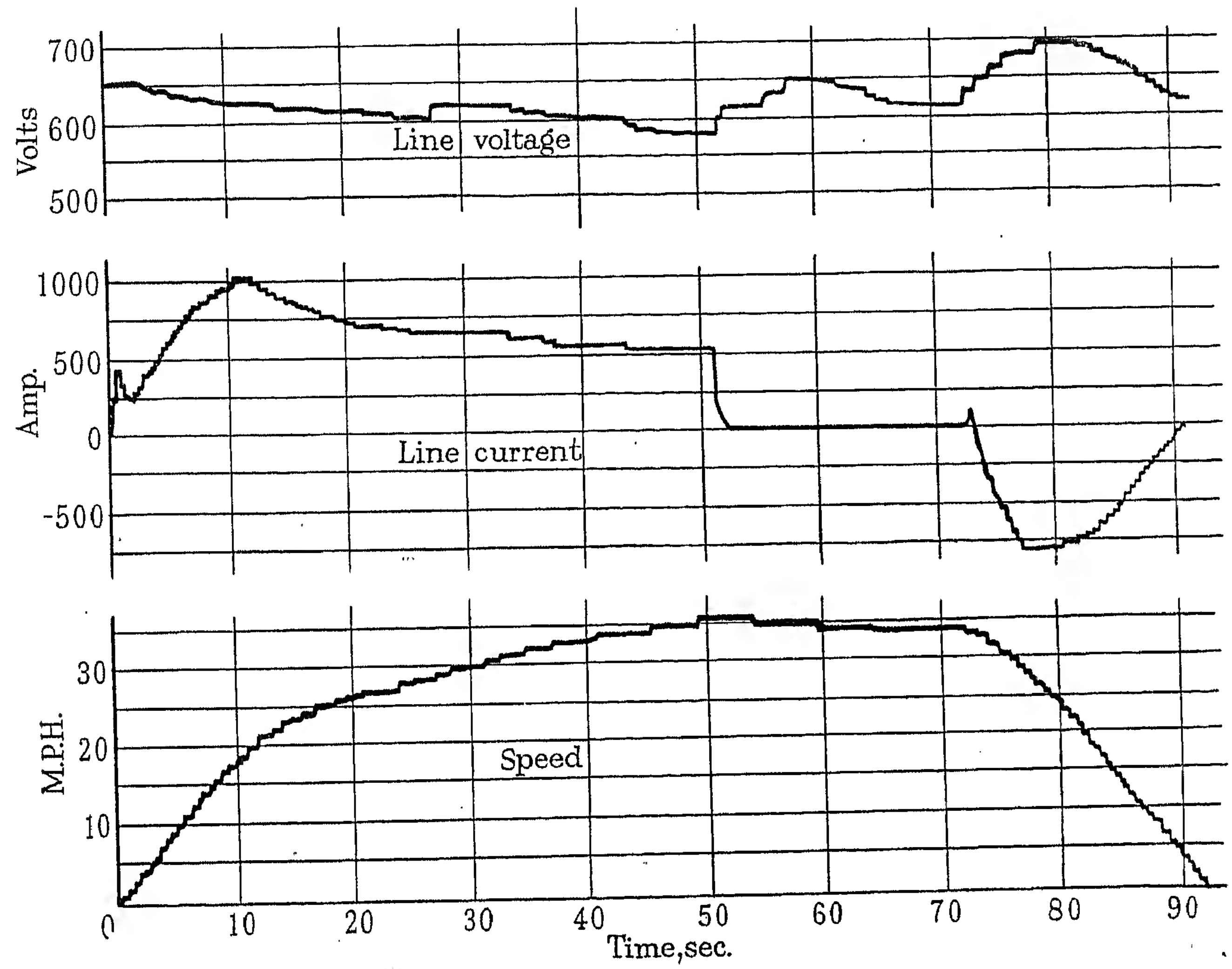

Fig. 20.—Recorder chart showing typical run with 6-coach train (recording measurements on one unit only).

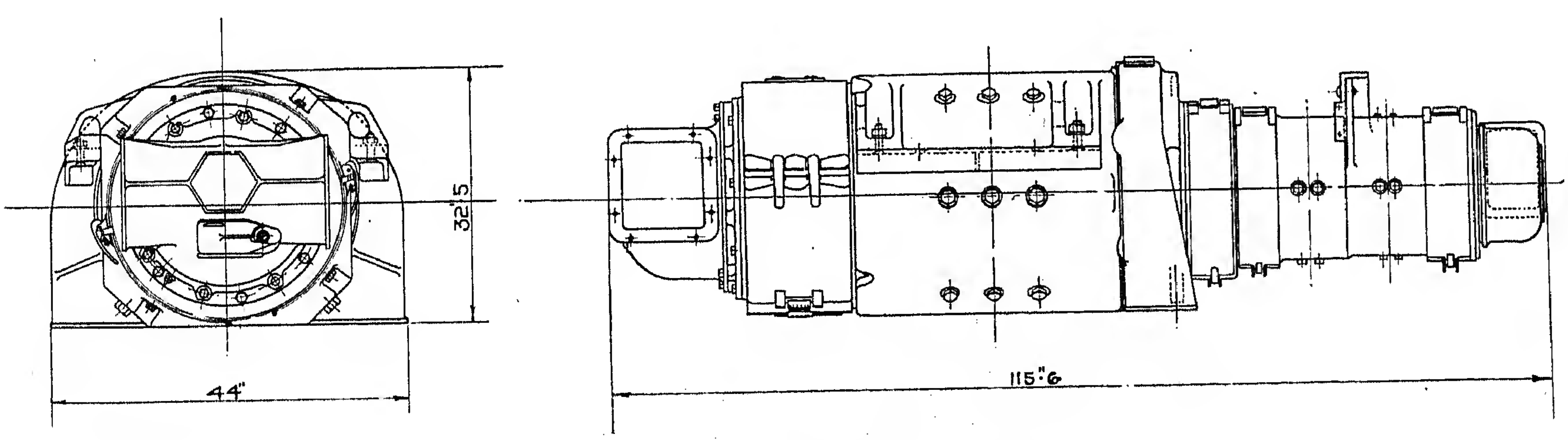

Fig. 21.—Outline drawing of MD53 metadyne.

The master controller is provided with three motoring

notches, giving (1) low initial acceleration and low balancing speed, (2) high initial acceleration and low balancing speed, (3) high initial acceleration and high balancing speed. Notch (1) is suitable for shunting purposes and for running in sections where the maximum demand on the line must be limited; Notch (2) is suitable for normal running in sections where the maximum speed must be limited to about 35 m.p.h.; and Notch (3) is suitable for all other cases where a high acceleration is required and where there are no special speed restrictions.

The regenerative-braking notches are combined with brake notches. They are used when the electropneumatic brake is cut out. In addition, beyond the service automatic Westinghouse brake position there is an emergency brake notch. If the brake-controller handle is brought into this position with regeneration and the electropneumatic brake cut in, regeneration is automatically cut out by the venting of the brake pipe and application is then made by combined electropneumatic and emergency automatic Westinghouse brakes.

All these brakes are operated from the brake con-

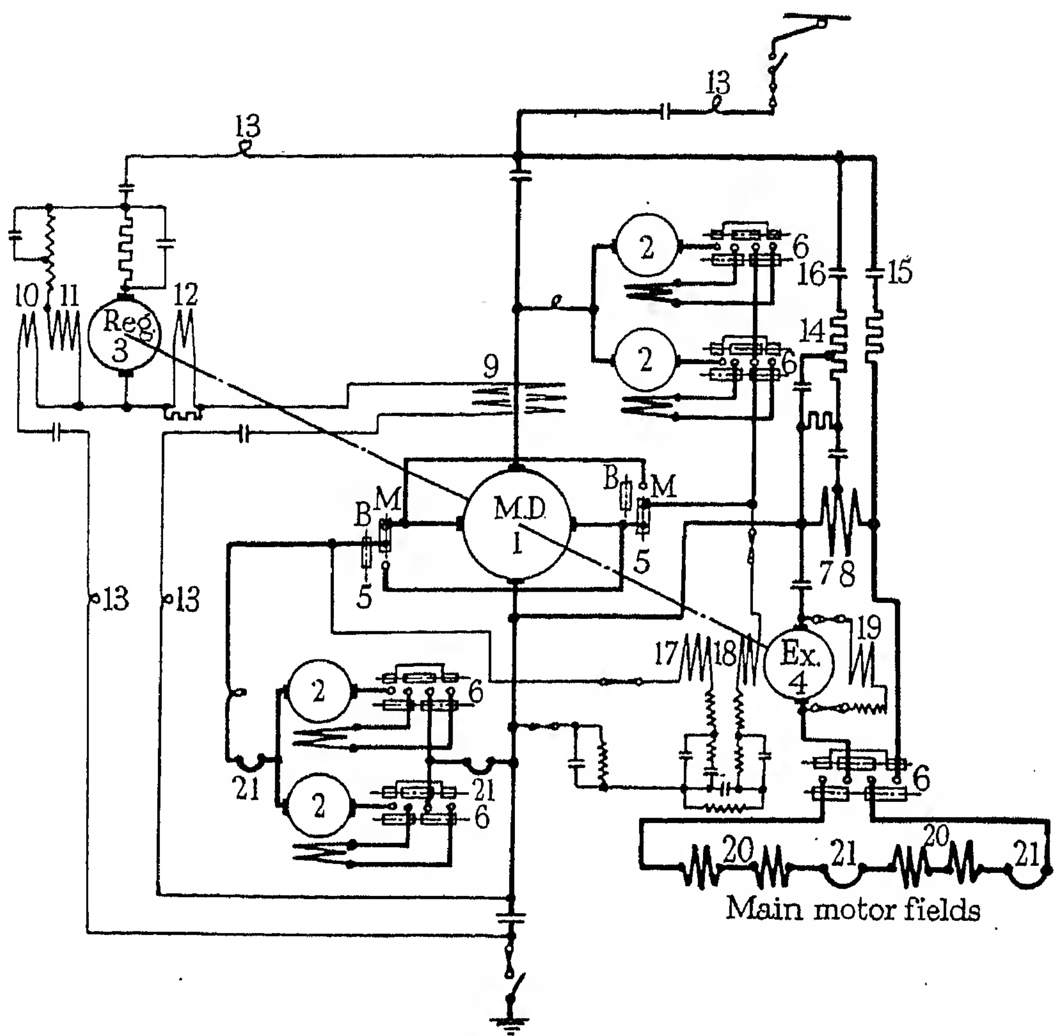

Fig. 22.—Diagram of connections of 2-coach units for latest equipments using metadyne Type MD53.

1. Metadyne.
2. Four motors, connected two pairs in parallel in reversible " 8."
3. Regulator dynamo.
4. Exciter for motor fields and variator.
5. Motoring-generating change-over drum switch.
6. Reverser drums for motor series and separately-excited fields.
7. Part of variator winding used for " entry " in regenerator.
8. Additional variator winding, used in " entry " in motoring.
9. Regulator winding.
10. Regulator series winding used in starting metadyne and coasting.
11. Regulator dynamo shunt winding.
12. Regulator dynamo reversed series winding used in working with metadyne.
13. Overload protection.
14. Resistance used for rheostatic braking in case line circuit opened.
15. Contactor used in " entry " in motoring.
16. Contactor used in " entry " in regeneration.
17. Exciter winding supplied from motor voltage.
18. Exciter winding supplied from difference between motor voltage and line voltage.
19. Exciter shunt winding.
20. Traction-motor separately-excited fields.
21. Couplers between coaches.

the Westinghouse electropneumatic brake and are operated by the same handle. There are two regenerative-braking notches, the first giving a low rate of deceleration suitable for checking the speed of the train, e.g. when approaching signals, whilst the second notch gives the maximum regeneration possible and simultaneously applies the air brakes to the non-motored axles.

Should regeneration fail, air brakes will also be applied immediately on the motored axles. Automatic Westinghouse brake positions, lap and service, are provided beyond the combined regeneration and electropneumatic troller, but the application of the brakes in a normal stop, although initiated by the controller, is actually controlled by two mercury retarders which operate, when the braking rate is too high, first to stop the application and, if the rate is still too high, to reduce the application by blowing off air. It will be appreciated that if regeneration is available a smaller air application will be used than if the train is stopped on the electropneumatic brake only.

The separate control of braking on the motored and braking axles involved the provision of separate brake cylinders for motored and trailer axles.

Advantages of metadyne control as applied to urban passenger trains.

The advantages of the scheme are:—

(1) High and smooth acceleration.
(2) Reduction in energy consumption.
(3) Reduction in brake-shoe wear:—
  (*a*) Saving in maintenance of brake shoes and rigging.
  (*b*) Saving in maintenance of electrical equipment due to a reduction of brake-shoe dust.
(4) Increase in life of tyres.

The disadvantages are:—

(1) Increased weight of equipment.
(2) Increased cost of equipment.

Battery Third-rail Metadyne Locomotives

A very interesting proposition was put forward in regard to the utilization of the 6-car experimental train equipments, which were unsuitable for use in conjunction with the new metadynes and rolling stock. This was for a battery-line locomotive for use on permanent-way maintenance, tunnel construction work, cable-laying, etc., the locomotive being arranged to operate either from the 650-volt conductor rail or from a 320-volt battery, the motors in both cases being fed through the metadyne. The metadyne was also arranged for charging the battery from the 650-volt conductor rail.

Very little modification was required to the metadyne equipment, it being necessary only to rewind the regulator machine armature and metadyne regulator winding, and to re-connect one of the exciter fields in order to render these parts suitable for operation on the 320-volt battery. The traction motors did not require any modification.

Fig. 23 shows the diagram of connections for this locomotive. The metadyne may be supplied either from the line or from the battery, and in either case the motors are connected in " right-hand eight " connection. In this case the speeds were so low that regeneration was not required, and there is therefore no need for reversal of the connections of the motors to the metadyne.

A drum-type switch is, however, provided which disconnects the motors from the metadyne, and connects the battery directly across the metadyne secondary when charging of the battery is required. Other contacts on the same drum modify the exciter field connections, and cut out the excitation of the traction-motor fields to suit

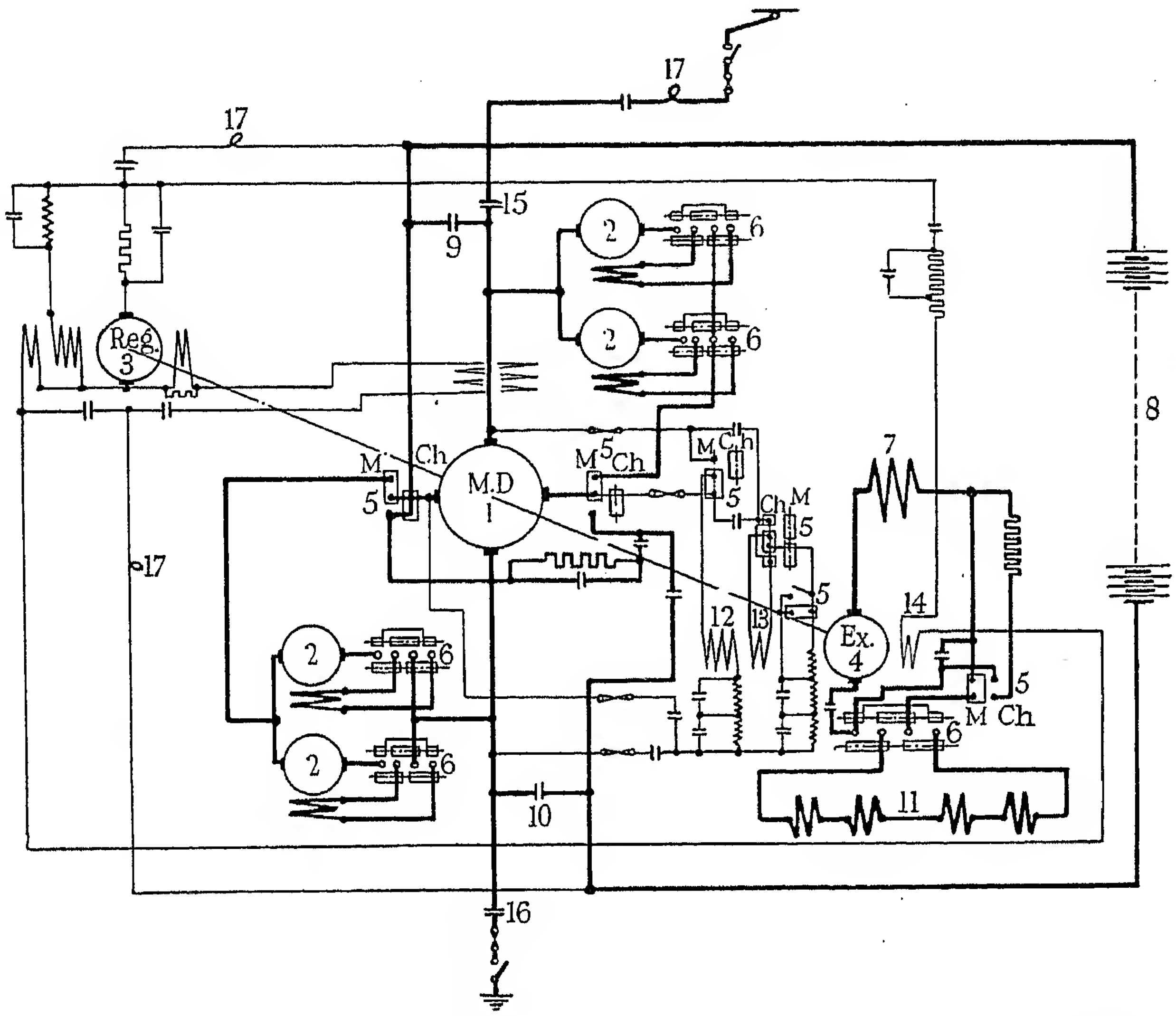

Fig. 23.—Diagram of connections of battery-line locomotive using metadyne Type MD52A.

1. Metadyne.
2. Four motors, connected two pairs in parallel permanently in right-hand " 8."
3. Regulator dynamo.
4. Exciter for motor fields and variator.
5. Change-over switches for running or charging battery.
6. Motor-field reversing switches.
7. Variator winding.
8. Battery.
9 and 10. Contactors for supply from battery.
11. Traction-motor separately-excited field.
12 and 13. Exciter fields fed by voltages derived from the metadyne.
14. Exciter field derived from the battery and used for " entry."
15 and 16. Contactors for supply from line.
17. Overload protection.

the "charging" condition. The various contacts on this drum are all numbered (5) in Fig. 23.

The arrangement of combinations and notches provided by the controller gives a very flexible locomotive, the operation being as follows: The master controller is provided with three handles—a forward and reverse handle, a combination handle, and the usual accelerating notch handle. The combination handle is provided with five positions, namely battery charging; motoring on battery "slow"; motoring on battery "fast"; motoring on line "slow"; motoring on line "fast." For each of the four motoring combinations the accelerating handle provides five smoothly-graded notches. For battery charging the accelerating handle is moved into a single position in the reverse direction, and this automatically gives a boosting charge up to the battery gassing point and thereafter a normal finishing charge, the change-over being made under control of a voltage relay. By means of a separate switch which is normally only used by the shed staff, a still lower rate (about half the normal finishing value) can be obtained for giving an occasional conditioning charge. Provision is also made for an extra-high rate of charge for emergency use. Thus the following rates of charge are available: Emergency or boost charge, 250 amp.; normal charge, 144 amp.; finishing charge, 70 amp.; conditioning charge, 30 amp.

When the system is working from the battery the use of the metadyne enables economical operation to be obtained by the elimination of starting resistances, particularly when the steady creeping speeds provided by the "battery slow" combination are in use, these low speeds being essential for such purposes as cable-laying.

Shunting Locomotives

Metadyne control would appear to be even more suitable for application to shunting locomotives than to suburban service. Consider for a moment the requirements of a locomotive of this type. A shunting locomotive is required to move heavy trains over short distances; the average distance travelled per operation may be only 100 yards or less. It is therefore important to use the adhesive weight to the maximum possible extent, and it has been found on actual tests that, owing to the absence of current peaks, greater loads can be pulled by a given weight of locomotive when metadyne control is adopted. In addition it will readily be appreciated that on shunting service a large part of the operating time is spent in running at low speeds, which for ordinary locomotives means running on the starting resistances, at low efficiency. With the metadyne control, as there are no resistance losses, the efficiency is very high indeed.

Another important consideration in shunting service is that whereas with a normal equipment the current taken from the overhead line is a maximum at the moment of starting, with the metadyne control the current taken from the line is a minimum at the moment of starting, thereby reducing very considerably the amount of burning of the overhead wire which is liable to take place when there is no movement between the collector and the overhead line. Further, with the standard method of control the heavy starting currents are continuously being dealt with by contactors. With metadyne control there is no interruption of main current. Control is effected by regulation of the field system, involving currents which may amount to only a few amperes.

Actually, shunting service was one of the first applications for which the metadyne principle was adopted, on a 55-ton shunting locomotive for the Paris–Orléans Railway. The locomotive had originally been supplied with the ordinary equipment for a 600-volt line, but when the voltage on the Paris–Orléans line was changed to 1 500 volts it was required that the shunting locomotive should meet the following conditions: (1) It should use existing (600 volt) motors. (2) It should operate on 600 volts from the third rail or on 1 500 volts from the overhead line. (3) It should operate on a 300-volt battery at reduced speed and reduced torque. (4) The metadyne must also recharge the battery while operating on the 1 500-volt overhead line.

The change was made, and proved so satisfactory that after about 2 years' operation the Paris–Orléans Railway placed an order for 2 more locomotives to be converted, and finally for a further 11, making 14 locomotives in all.

For the tests which were carried out by the Paris–Orléans Railway, the total train was made up of one 55-ton metadyne locomotive; one 72-ton locomotive with standard équipment; and sufficient wagons to bring up the total load to 500, 450, and 400 tons respectively, for three tests; the total load in each case being moved first with the 72-ton locomotive and then with the 55-ton metadyne locomotive.

Maximum-load tests were made by increasing the weight of the train load, and it was found that skidding took place on a given grade with the same train load using either a 55-ton locomotive with metadyne control, or the 72-ton locomotive with normal control. Careful measurements confirmed that an increase of adhesion of about 25 % was obtained. This is due to the fact that the torque with the metadyne control is perfectly even, whereas with the normal control the peaks start the wheels slipping. The increase of adhesion obtained was a little higher than could be accounted for by the excess of the peak current over the mean, as the latter figure was only 15 % to 20 %.

On current-consumption tests it was found that the average reduction in current for different services varied between about 28 % and 38 %, this being due to the absence of rheostatic losses.

Diesel-electric Locomotives

In the application of the Diesel engine to traction, it is necessary to arrange automatically to control the excitation of the generator so as to maintain the engine load constant. One well-known principle on which this may be done is to provide an exciter (or some other speed-sensitive device) to control the generator field-strength, the exciter supplying a voltage which varies very steeply with change of engine speed, so as to raise the load when the engine speed tends to increase and to reduce the load when it tends to decrease. In such schemes a metadyne may be used with great advantage as the exciter, introducing a field-forcing action which

tends to overcome the inductance of the generator field and to ensure that it follows the indications of the tachometer exciter with very little lag.

A diagram of connections for a Diesel-engined shunting locomotive employing the metadyne as an exciter in this way is shown in Fig. 24.

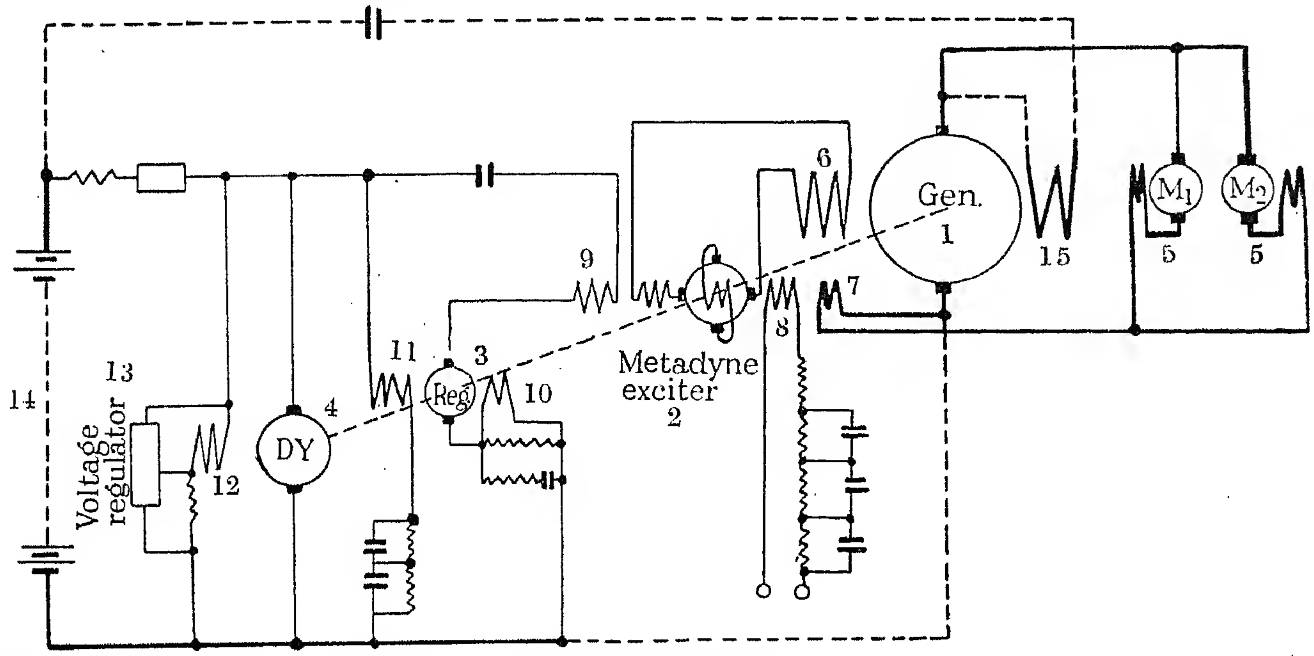

Fig. 24.—Diagram of connections showing a metadyne used as exciter for main generator of Diesel-electric shunting locomotive.

1. Main generator.
2. Metadyne exciter.
3. Regulator dynamo arranged to adjust load automatically to keep speed constant.
4. Dynamo for battery charging.
5. Traction motors.
6. Main-field of generator.
7. Series field of metadyne exciter fed with main generator current.
8. Separately excited field of metadyne exciter.
9. Regulating field of metadyne exciter.
10. Reversed series winding of regulator dynamo making current variation sensitive to speed-changes.
11. Separate excitation of regulator dynamo.
12. Field winding of supply dynamo.
13. Voltage regulator.
14. Battery.
15. Starting series field of main generator.

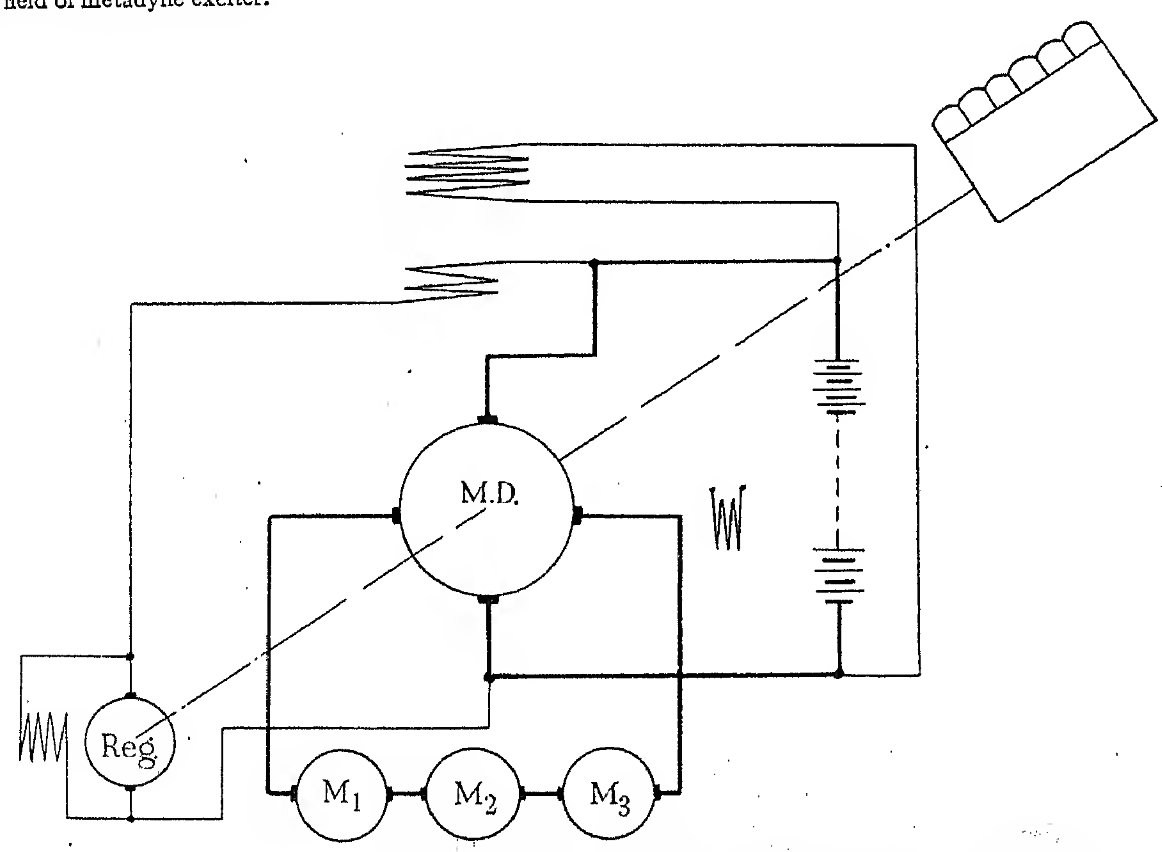

Fig. 25.—Diagram of connections for Diesel-metadyne-battery locomotive.

On the same shaft as the main generator are mounted a metadyne exciter and two other small dynamos. One of these, marked DY in Fig. 24, is maintained at a constant voltage by a voltage regulator, and keeps the battery charged that is used for starting the engine and for the auxiliary current supply. The second small dynamo is analogous to the regulator dynamo on the metadyne transformers, except that its back e.m.f. is opposed to the constant voltage of dynamo DY instead of to the voltage of the line. It has a reversed series winding to increase the change of current resulting from a given change in speed.

The winding of the exciter metadyne which is supplied in series with this regulator machine is, in this case, a

variator winding. The exciter metadyne acts as a relay, and when the current in this variator winding, for example, increases, the exciter metadyne applies a very high voltage to the generator main field until the current is brought back to normal, a "field forcing" action being obtained to overcome the inductance of the generator field. The whole arrangement ensures that the generator voltage is automatically and rapidly adjusted to prevent any change in speed, i.e. adjusted to the output of the engine and so as to maintain the speed constant.

A special series winding is provided on the main generator which is used in starting the engine from the battery.

Diesel-electric-battery Locomotives

On services in which a limited amount of running is required away from the overhead line, particularly for yard shunting where it would be uneconomical to provide overhead line for all the sidings, the very useful Diesel-electric-battery type of locomotive could be provided, for which a generator of the metadyne type serves very well.

It was found in one application which has been investigated that although the maximum duty of the locomotive required 150 h.p. at the wheels, the average load for the whole day was not more than about 15 h.p. This means, of course, that for an ordinary Diesel locomotive a 150-h.p. engine would have to be supplied to take care of the peak load, which is only on for very short periods. If some way could be found of providing this peak load for a short period, an engine of about 20 h.p. would be ample. A scheme which can be used to this end is shown in Fig. 25. The metadyne is mechanically coupled to the Diesel engine, the primary being connected across the battery whilst the secondary is connected to the traction motors. In this case the regulator dynamo controls a "primary variator winding" and causes the primary current to increase or decrease according to the amount by which the speed falls slightly below or rises slightly above normal. Thus the speed is kept nearly constant, whatever the motor demand or even if the motors regenerate, the balance of load being supplied or absorbed by the battery.

The operation would be as follows: With the locomotive stationary the full output of the metadyne would be used in charging the battery. When the energy required by the motors exceeded the value corresponding to the maximum torque of the engine, the battery would automatically operate in parallel with the engine, and supply the extra power through the metadyne to the traction motors. This would be done quite independently of the driver, who would not need to think about anything more than moving his controller to give the required speeds, the metadyne taking power from the battery quite automatically. As the battery discharge would only be required for short periods, a comparatively small battery would serve the purpose.

An additional advantage of this scheme is as follows: with a battery of a type such as will accept heavy charging rates, the scheme permits regenerative operation, and all braking can be done regeneratively. It will therefore be possible to reduce the amount of use made of air brakes, and the adoption of regenerative braking would reduce slightly the size of Diesel engine required. In certain cases, if the engine failed the battery could be used to operate the locomotive for limited service.

ACKNOWLEDGMENTS

The authors would like to express their appreciation of the contribution made by the engineers of the London Passenger Transport Board to the successful development of the metadyne for the operation of the trains on the Board's systems. The authors' thanks are due to the Board for permission to publish the data which have been obtained on their system, both on the experimental trains and on the equipments as finally installed. Acknowledgment is also made to the Publication Department of the Metropolitan-Vickers Electrical Co., Ltd., for assistance in editing the paper, and to Mr. E. Webster for assistance in preparing the material.

DISCUSSION BEFORE THE INSTITUTION, 23RD FEBRUARY, 1939

Mr. C. E. Fairburn: The metadyne has been running for some time on the Barking–Upminster line, so I am able to speak not entirely without knowledge of its operation.

Dealing first with the principle of the metadyne, attempts to obtain constant accelerating current have been made for years. We have considered multi-notch control systems and even single-phase systems with rectifiers, but this is the first time that current convertors for this purpose have been put into operation on a large scale. The metadyne combines in one equipment a steady accelerating current with the ability to regenerate.

I should like to consider the metadyne from the point of view of equipment maintenance. As far as the motors are concerned their deterioration is largely that of their insulation and this depends to some extent upon the number of times the copper expands relative to the insulation, i.e. upon the number of times heavy currents are switched on. Since with the metadyne regeneration is used and the current is switched on twice between starting and stopping, I should expect the time between motor rewindings to be shorter than with rheostatic equipments. Again, and this perhaps is of greater importance, the life of the shafts, gears, and bearings depends on the amount of work they are made to do, and with the metadyne system they are loaded twice between stopping and starting. As the motors have to regenerate, the r.m.s. current values will naturally be higher and larger motors must be used. All this means that the equipment will be more expensive than with the rheostatic system.

In the early days of the metadyne it was said that it did away almost entirely with control equipment, but Fig. 22 shows that for 4 motors the metadyne equipment has 3 commutators, 17 contactors or switches, and 7 reversers. I do not think, therefore, that the amount of equipment is less than with the ordinary rheostatic arrangement.

It is agreed that, with the metadyne, savings are obtained in energy, brake blocks, and tyres. It is necessary to offset these savings against the extra maintenance and capital costs, and there must be some length of section between start and stop where the two balance out. It would be interesting if the authors could give their views as to where this point occurs.

The metadyne is a constant-current machine, and for the same adhesion it makes possible about 10 % greater acceleration than that of a conventional rheostatic equipment. Most modern equipments give an acceleration of 1·3 to 1·5 m.p.h. per sec., and what is generally being sought is not a 10 % increase but an acceleration of 2 to 2·5 m.p.h. per sec. To get this, more adhesive weight is required, i.e. it is necessary to motor more axles, and if this is done the desired acceleration can be obtained with rheostatic equipment.

I am not quite clear as to what is the minimum amount of apparatus it is necessary in practice to add to a rectifier substation to enable it to accept regenerated energy. On the South African Railways where this is required two tanks instead of one have been installed, and this clearly means an increase in capital cost.

On page 371 I notice the equation $V_1 = kI_2$, which means that the motor current varies directly with the line voltage. On traction systems the line voltage is by no means constant and if, as is not unknown, a substation goes out of service for a time the accelerating current will be less than normal. Under such circumstances a train leaving a station will take a longer time to clear the station signal. With rheostatic equipment, on the other hand, the initial acceleration is not affected by a drop in voltage. Therefore it seems that if a service is timed on the basis of a metadyne working with normal acceleration, and a substation drops out and so reduces the voltage, it will dislocate the service to a greater extent than with rheostatic equipment.

Prof. J. M. Pestarini: The new type of machine described by the authors is the result of an investigation by means of equations interpreting the operation of a rotating machine which is regarded as having the general form of the dynamo on direct current. Although such machines were first built in France, metadynes have found their widest application in England.

The field of application of the metadyne is not limited to traction, and I do not think it will be long before we hear of British engineers who are able to give information about the application of the metadyne in other fields. The variety and flexibility of the inherent electromechanical characteristics of the metadyne, and its dynamic property of quick response, will attract, I hope, the interest of British engineers for some time to come.

Mr. J. E. Calverley: The authors' demonstration and their verbal summary of the paper reminded me of the Thury machine of 30 years ago, of which Mr. Fletcher and I had considerable experience. This machine also was controlled by armature reaction, the axis of which was determined by the movement of brushes. Thury generators supplied similar motors in series with a constant current, and the motors could be braked down to zero and reversed. All machines controlled by armature reaction introduce problems in commutation, and this must be a difficult point in the metadyne, where the armature reactions are unbalanced.

Fig. 10 shows the armature reaction along one axis only. If we plot the armature reaction also along the other axis, one being constant and the other variable, we obtain a more complete picture of the field condition, which suggests that the design of the interpoles will be rather a tricky business.

The authors' diagrams show that the secondary current of their machine is really the magnetizing current 90° out of phase with the line current, and that it builds up the back e.m.f. of the metadyne machine. This back e.m.f. must be opposite to and almost equal to the line voltage, and will vary with it. I notice that the line voltage varies from about 570 to 700 volts, and I should like to know what provision is made on the metadyne machine to compensate for the changes of line voltage.

It is unfortunate that the paper does not include a diagram to show the current and voltage conditions in the motor circuit for one particular set of conditions. The diagram which is given shows only the current taken from the line, and does not indicate the conditions in the motor circuit.

The authors omit to deal with the question of efficiency. All the time that the train is in service, including those periods when it is standing still, the metadyne is consuming energy, and there are in addition all the losses in the metadyne group of machines when the train is actually running.

The authors state that the regenerated energy amounts to 25 % to 30 % of the motoring energy when measured at the train. That, I presume, is the energy input to the metadyne, and I should like to know what saving it represents in comparison with an equipment having normal resistance control.

Finally, I should like to know how many train wires are required to enable metadyne equipments to run in parallel on multiple-unit stock.

Mr. H. Charnley: There is no doubt in my mind that the operating characteristics of the metadyne are exactly what are required for electric traction, although they are obtained by means of a very complicated machine and control gear. I thought at first that the main complication of the system was due to the fact that separately-excited traction motors are used to obtain the regenerative feature. It looks to me as if fairly similar operating characteristics could be obtained by an automatic counter voltage system. In this connection I should like to refer to a machine developed by Burge and Macfarlane,* manufactured by Messrs. Crompton in 1911, and applied to traction. It was like the metadyne in this respect, that a 2-pole machine had four sets of brushes, and the secondary current set up a flux which produced the back e.m.f. on the A and C brushes. It had a high output-coefficient and efficiency, but its development did not go much beyond the experimental stage, because the designers came to the conclusion that similar characteristics could be obtained by a straightforward machine like a motor-generator set, and they expected they would have considerable commutation difficulty in larger machines. They came to the conclusion that a straightforward motor driving a generator, this generator being

* *Journal I.E.E.*, 1912, vol. 49, p. 93.

in series with a traction motor across the line, and finally building up in the reverse direction, would be a better proposition. This set would have a very high output-coefficient, with high efficiency; for instance, if the driving motor of the set had an efficiency of 90 %, and the generator had an efficiency of 90 %, the combined efficiency would not be 81 %, but 90 %.

How would a machine of this sort compare in weight with a metadyne suitable for handling the same load? From the paper I estimate that the metadyne would probably weigh between 8 000 and 9 000 lb., and it seems to me that a motor-generator set could be constructed to handle four such motors which would not weigh more than 9 000 lb. These machines would have the advantage of being perfectly straightforward in design and of having a high efficiency. The constant output current referred to in the paper could be obtained by the use of suitable shunt-field contactors and an accelerating relay, and if plain series motors were used it would be possible, regardless of the speed of the train, to close the main contactors without giving rise to surge currents. Nowadays, in view of the high rates of acceleration and braking which are adopted, no operator would be prepared to go to the expense of employing rotating machinery without some compensating advantage such as regeneration, but in many cases the regenerated current is an embarrassment owing to the non-receptivity of the line. The use of separately-excited motors would make the system which I describe regenerative, but there would be certain entry problems with which it would be necessary to contend.

I understand that the metadyne is a 2-pole machine, and it is probably of fairly large diameter. This type of machine will, of course, have very big overhangs to the armature windings owing to the large coil pitch, and this will tend to bring the efficiency down. It requires a very deep armature core, and probably the use of a sleeve will be impossible because of this depth. As there are five sections on each field coil, and a large amount of insulation is required between the sections, the space factor must be very bad.

I do not think that the characteristics of the metadyne are suitable for locomotives, because in a locomotive the current should be entirely under the control of the motorman, and it should not have a constant value. For this application a motor-generator set as outlined above would appear more suitable.

Dr. E. Rosenberg: What alternatives to the metadyne are available if one wishes to adopt regenerative control? There is, first, the possibility of additional shunt windings or of exciting the series windings of the traction motors by means of a separate exciter and returning power to the line direct. This gives regenerative control, but not down to such a low speed as does the metadyne. So far as starting and stopping are concerned, a motor-generator with Ward–Leonard control is as satisfactory as the metadyne, and it would be interesting to obtain figures as to the saving in weight and efficiency obtained by adopting the metadyne. The advantage should be comparable to that of a rotary convertor over a motor-generator.

The losses in an armature winding with two sets of brushes can be calculated on the assumption that they are caused by the root mean square of both currents, as in the case of two alternating currents with 90° phase difference. A similar problem is that of the cross-field machine for train lighting, for which I suggested in 1905 the expression "two-phase direct-current machine."* The metadyne has the advantage of requiring only one commutator, but this is countered by the disadvantage that the number of brush arms is doubled and that the full voltage occurs during part of the run between any two adjacent brush-arms. In practice, therefore, a smaller number of poles will probably be used in the metadyne than in an ordinary machine. Nevertheless, there is every reason to believe that the metadyne has real advantages for the purpose of converting a constant d.c. voltage into a variable d.c. voltage.

Mr. W. S. Graff-Baker: In reply to Mr. Fairburn, I feel confident that despite—and because of—the fact that it is switched on twice as often as an ordinary traction motor, a metadyne motor is less likely to suffer deterioration due to temperature-changes, since the average change in temperature must naturally be less.

The question of brake blocks is one of the London Passenger Transport Board's chief preoccupations. With 3 000 cars in service, we grind to powder some 4 000 tons of cast iron every year, and this not uncommonly finds its way into the electrical equipment. Taking the average car miles per brake block, we obtained with the old stock running on the Hammersmith and City Line 540 miles, whereas from the metadyne stock we get 800 miles with a heavier train and a slightly higher speed at the point of braking, and this despite (at present) a relatively small proportion of regeneration. The savings are not only in brake-shoe dust and the difficulties which it causes, but also in the cost of the brake block and the labour of putting it on.

Many speakers have professed to be horrified at the amount of electrical equipment required to control the metadyne. The contactors must, however, be counted with due regard to their size, and it must be remembered that modern contactors do not give much trouble. With regard to the number of reversers, this was increased because we prefer not to put four motors on one car. We favour putting two motors on each car, one on each bogie, and in order to avoid power cables passing from one car to the other with a single equipment one has to divide the reverser and call it two reversers.

Turning to the question of substations, in the calculations precedent to the adoption of the metadyne we did not count on any energy being absorbed by the substations, and with 40 trains an hour, or even with 20, it is not very difficult to ensure that all the regenerated energy is fed into trains in the same section. In our calculations we excluded entirely those times of the day when the traffic was light, and also certain parts of the line which were not receptive.

I should like to mention that the current saving cannot be measured except at the substation, and it cannot be measured satisfactorily unless a considerable proportion of the service is running as a metadyne. It is our intention very shortly, now that we have a considerable proportion of trains on a particular line using the metadyne,

* *Elektrotechnische Zeitschrift*, 1905, vol. 26, p. 393.

to record the substation input to the track for one week without regeneration and for another week with regeneration.

Mr. F. V. G. Bird (*communicated*): I should like to give some further information regarding the metadyne shunting locomotives of the Paris–Orléans–Midi Railway, two of which were already in service in 1933.

These locomotives operate from an overhead catenary and not from either a third rail or a battery, as was suggested by the authors in their introductory remarks. The maximum metadyne secondary voltage is approximately 1 100 volts across all four traction-motor armatures in series. The metadyne, which is cross-connected with displaced secondary brushes, has a continuous rating of 105 kW, giving approximately 870 volts, 120 amp., at 995 r.p.m.; and the unit weighs 6·25 tons with the regulator machine. The metadyne primary brushes are especially made laminated to improve the commutation, which is now very satisfactory. Both primary and secondary commutating poles are fitted, also primary and secondary stabilizing windings. The metadyne is excited prior to paralleling on the primary side by a special winding excited from the locomotive control battery. The paralleling takes place automatically under the control of a paralleling relay.

I give below a few comparative performance figures for the B + B metadyne locomotive weighing 53·5 tons and a standard B + B locomotive with rheostatic control weighing 72 tons.

(*a*) Hump shunting service, train weight from 800 to 900 tons, average speed 1·5 to 2 km. per hour: B + B locomotive, 98·5 watt-hours per ton shunted; metadyne locomotive, 62·5 watt-hours per ton shunted.

(*b*) Ordinary shunting service: B + B locomotive, 30 watt-hours per ton shunted; metadyne locomotive, 21 watt-hours per ton shunted.

These locomotives can exert a tractive effort of 16 tons at the rail, or a braking effort of 11 tons. The regenerative braking is the service brake and is normally employed down to rest. Air brakes are fitted to comply with the regulations and for emergency use.

These locomotives were built in 1906 for service on the 600-volt Orsay–Austerlitz tunnel service, and the original frames, bodies, and traction motors (with a different gear ratio, however) are embodied in the metadyne locomotives. The traction motors still have no interpoles, and were reconditioned by the railway company in their own workshops. The frames have not been seriously reinforced. It has thus been possible to bring into service equipment which had been rendered obsolete by the change to 1 500 volts, at a relatively very low cost. Extremely successful results have been obtained, and much credit is due to the Paris–Orléans–Midi Railway for their initiative in thus being the first to apply the metadyne to electric traction.

Mr. J. C. Macfarlane (*communicated*): The *name* "metadyne" given to the special type of d.c. convertor described in this paper probably was invented by Prof. Pestarini, but I doubt whether the authors' statement that he was the inventor of the machine itself can be fully justified. Great credit is certainly due to Prof. Pestarini for his work in adapting the metadyne for traction and other purposes, but there are others who have also done pioneering work, among whom may be specially mentioned Messrs. Brown-Boveri, Bruce Peebles, la Cour, and Macfarlane and Burge. I find that the record of an invention,* now 32 years old, foreshadows practically every development in connection with the metadyne which is indicated in the present paper.

About 30 years ago, P. D. de la Cour invented a form of split-pole convertor similar in many respects to the metadyne† but provided with compensating windings in all the part poles for annulling the armature reaction effects on these, and using other windings to produce approximately constant current in a secondary circuit. About the same time Messrs. Crompton were manufacturing, to the designs of Messrs. Macfarlane and Burge, another form of convertor on what are now known as metadyne principles, which was chiefly used to supply constant current to arc circuits.

Turning now to the machine described by the authors, it is, in its simplest form, a split-pole, split-field, bipolar dynamo-electric machine, with two sets of brushes lying in planes at right angles to one another, the planes passing symmetrically through the spaces between the poles (see Fig. A). Another form of convertor, having working properties similar to those of the metadyne, is indicated in its simplest form in Fig. B. It differs from the metadyne in that, although the field structure is still bipolar, the armature has a 4-pole winding or its equivalent, i.e. two 2-pole windings of approximately half the normal coil span. No. 1 machine (the metadyne) may therefore be called a split-field type, while No. 2 is undoubtedly a split-armature unit. A comparison of the two will show that if both were fitted with "variator" and stability windings, No. 1 would require four, whereas No. 2 would require but two separate coils on each polar limb. The interesting fact also emerges that the reverse condition exists in the armature circuits, i.e. machine No. 2 requires, for perfect commutation, two interpole coils per interpolar limb, compared with one on the metadyne. Although the second unit has all the operating properties of the metadyne, it appears to be simpler in construction, and its method of working is easier to understand. For instance, the flux emanating from each pair of polar limbs (in what may now be called the motoring poles) controls the back or motoring e.m.f., and that from the remaining pair controls the generator or secondary e.m.f.; and therefore:—

(1) The design of the motoring and generating axes can proceed along conventional lines, due regard being given to the condition that the motor armature may magnetize the generator field system, and the generator armature may magnetize the motor field system in whole or in part.

(2) Because it is unnecessary to distribute the field winding over all polar limbs, the secondary "variator" windings can be simply modified to stabilize the speed and take the place of the pony motor; and with a few turns of winding on the motoring poles, starting and entry of the convertor can be simply accomplished.

Further comparison between the two types reveals:—

(3) Principally owing to the shorter armature end lengths, the copper losses will be less in No. 2, whereas,

* British Patent No. 9146—1908 (Brown, Boveri and Co.).
† British Patent No. 24187—1909.

owing to the smaller back iron section required in the metadyne, the iron losses will be less (other considerations being the same in the two cases).

(4) The distribution of armature heating on load is more favourable to the second machine. (This is shown in Fig. A.)

(5) Owing to the shorter armature evolutes and the absence of the pony motor, the second convertor will usually be the more compact (and in some applications the space occupied is a major consideration).

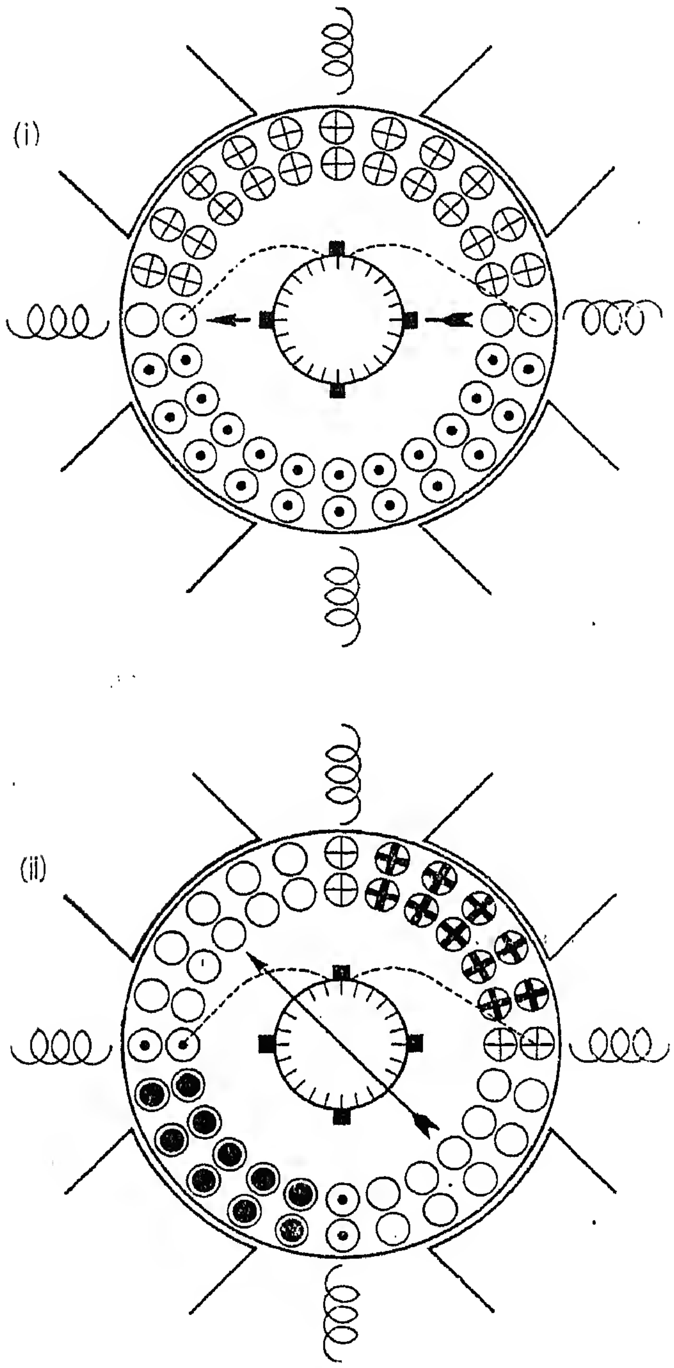

Fig. A

Figs. A and B illustrate the points discussed; (i) and (ii) refer to the unloaded and loaded conditions respectively, the loaded condition being based on the assumption of equal currents flowing in primary and secondary circuits. The brushes are shown in the actual positions which these would occupy on the assumption of equal-limb, diamond-shaped armature coils (indicated by dotted lines in Figs. A and B), and the general directions of the armature m.m.f. and flux paths are indicated by the large arrows.

Fig. A(ii) (metadyne loaded) shows the bunching of the armature wires into two opposite sections of the armature winding. The polar limbs through which the arrow passes hold all the magnetic loading for this condition, and therefore the m.m.f.'s on the other pair of limbs are in complete opposition. It is interesting to note that the magnetically-loaded pole parts are opposite unloaded parts of the armature surface, indicating (correctly) a condition of no mechanical torque.

Fig. B(ii) (second machine loaded) shows different distributions. The m.m.f. direction arrow now passes between the polar limbs, indicating that the m.m.f.'s of the interpole coils must be cumulative in this direction and in opposition in a direction at right angles.

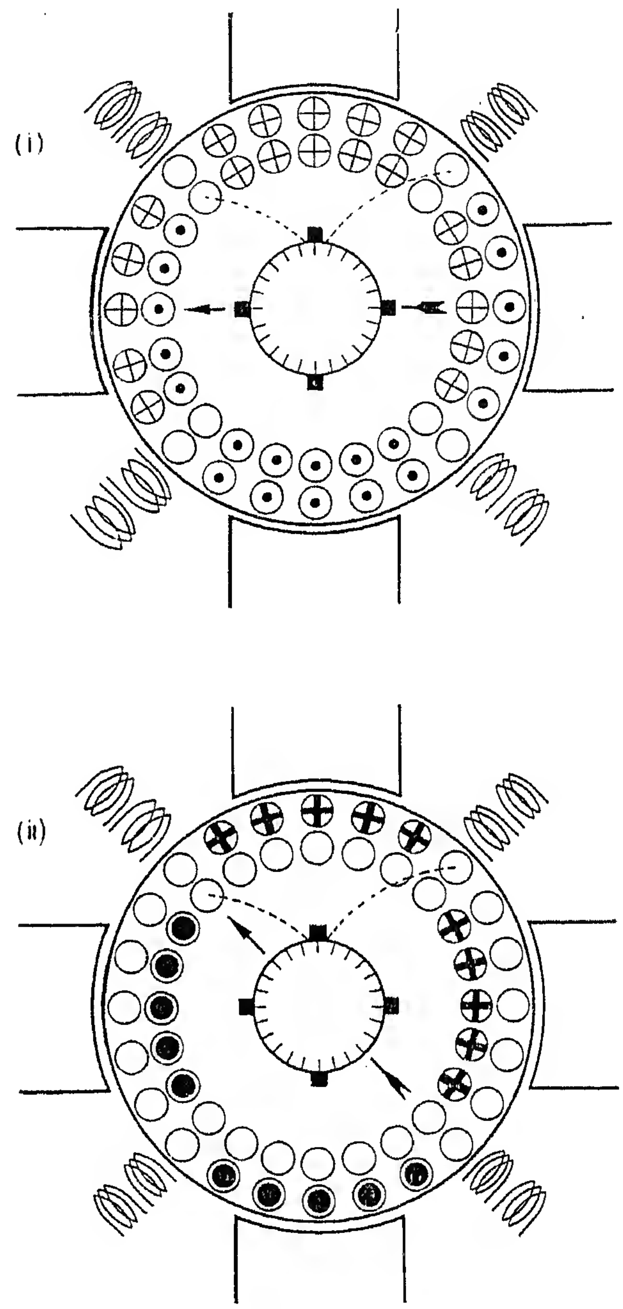

Fig. B

The split-armature unit has not been applied to traction, but many of these units have been used with success for many years for controlling cranes, winches, capstans, windlasses, and the like, on some of the most important passenger liners recently built, including the "Normandie."*

I have gathered the impression from the present paper that a constant motor torque of a value up to the limit of rail adhesion should be aimed at during acceleration, and

* British Patent No. 308041—1929 (J. C. Macfarlane and W. A. Macfarlane); British Patent No. 405759—1934 (J. C. Macfarlane, W. A. Macfarlane, and G. Austin); British Patent No. 476398—1937 (J. C. Macfarlane and W. A. Macfarlane).

again that this must be varied considerably at the beginning and end of the acceleration period to secure the comfort of the passengers. Why is it, then, that the designers of Diesel-electric equipment try to get the full engine power to the wheels throughout the maximum range of speed? With rubber-tyred vehicles, where the question of adhesion does not arise to the same extent, would a constant-power or a constant-torque characteristic be the more suitable, provided that, in each case, reasonable acceleration rates were maintained at extremes of speed?

[The authors' reply to this discussion will be found on page 394.]

NORTH-EASTERN CENTRE, AT NEWCASTLE, 27TH FEBRUARY, 1939

Mr. W. J. C. Fletcher: The authors have chosen the names for the parts of the metadyne with great care, but it seems to me that it would be an advantage to give a new name to the "regulator motor." This is a rather confusing title, because the device to which it refers is really a special form of regulator, different from other kinds. To avoid giving a further burden to the word "regulator," I would suggest some such name as "regumotor."

Mr. F. C. Howlett: The authors showed a lantern slide of the one-cycle metadyne and its armature. With regard to the latter, they remarked that this is usually, but not necessarily, wound for two poles. What considerations govern the choice of the number of armature poles?

Mr. D. J. Watkins: The authors mention that the metadyne brake can be used down to a speed of 4 m.p.h. It seems to me that it would be very difficult to maintain a uniform rate of retardation when transferring at this speed to braking by the compressed-air brakes. Is it possible to work down to this figure of 4 m.p.h. in practice, or is it just a theoretical figure? How is the change-over effected? Can both forms of braking be applied to the axle at the same time?

Mr. V. Easton: Whilst the principle of the metadyne is ingenious and apparently gives characteristics suitable for application to problems in connection with electric traction, it seems that there must be some difficulty in the practical application. For example, no mention is made in the paper of the question of commutation. It would be interesting to have details of the methods adopted to overcome this difficulty and to know to what extent they have been successful. Again, there may be a greater tendency to flashover, particularly when switching on for regeneration, owing to the interposition of an additional set of brushes between the pair of normal brush-arms which, even if they do not affect the potential distribution around the commutator, will reduce the distance between brush-arms. How do the limiting conditions for design constants compare with those generally accepted for d.c. machines of equivalent output?

Referring to the authors' summary of advantages and disadvantages, since a saving in maintenance of electrical equipment due to a reduction of brake-shoe dust is claimed, the maintenance of the metadyne itself must be added to the disadvantages of increased cost and weight. The substitution of rotating machinery with bearings, commutator, brushes, and brushgear, for the normal control resistances must necessarily increase the maintenance. This may indirectly lead to a further disadvantage in respect of space, since the resistances may be mounted where convenient below the frame, whereas the metadyne, requiring periodic attention, should be mounted in a reasonably accessible and clean position.

Finally, it would be of assistance when considering Figs. 18 and 21 if details were given of the traction motors which are controlled by these metadynes.

Mr. J. Dickinson: The authors call attention to the smoothness of the speed/time characteristic obtained with the metadyne system. However, Fig. 20 shows many small discontinuities. Are these due to the recording instrument alone?

A short statement dealing with the efficiencies obtainable in practice with the metadyne control would be useful.

Mr. C. M. Beckett: I have heard a criticism made of many regenerative schemes (other than in mountainous districts where regeneration is an economic necessity), and that is, that in order to make a line receptive it is necessary to have motor-generator sets or to install resistances at the substations. It is quite clear, however, that in general regeneration is not essential, and it presumably pays to install this extra substation equipment.

What are the inherent characteristics of the metadyne in the event of a circuit-breaker in the substation failing to function? What would happen to the flow of regenerated energy if the voltage on the line were suddenly allowed to rise owing to an open-circuit? Would the regenerated voltage automatically rise and cause flashovers in the motors or in the distribution system?

Mr. I. Murray: Electric trains are able to provide rapid and frequent services on suburban lines where the distances between stations are short. To provide these services it is necessary to have high acceleration and severe braking, with the corresponding losses. With regard to braking by mechanical means, it may be of interest to note that in the North Tyneside electrified area some 12 000 brake shoes weighing 160 tons are used per annum. The brake shoes weigh 33 lb. each when new and are rejected when half worn away, so that some 80 tons of cast-iron dust is spread along the track. This dust is drawn into the motors and equipment and its removal necessitates additional maintenance work. It is very surprising to see the quantity of dust which is disturbed when the motors are stripped and blown out. The introduction and development of the metadyne is therefore very opportune and will very considerably reduce the dust problem.

Fig. 18 suggests that the metadyne is ventilated; has any special step been taken to exclude dust? On the debit side of the metadyne is the question of weight. This is rather important; any extra weight carried means extra consumption of energy. Traction motors weighing 2 tons can be easily removed or installed by means of an overhead crane. The metadyne unit is rather large; the length as given in the paper varies from 7 ft. 6 in. to 9 ft. 6 in., according to the size of unit, and the weight will be considerable. The removal or replacement of a

metadyne unit under a car does not appear to be such an easy matter as dealing with a traction motor. No doubt a special method has been devised for this work. It may be necessary to strengthen the underframe of the coach to enable it to carry a metadyne unit.

The large number of units installed by the London Passenger Transport Board will enable experience to be gained which will have a great bearing on the future application of the metadyne to electric traction.

[The authors' reply to this discussion will be found on page 394.]

TEES-SIDE SUB-CENTRE, AT MIDDLESBROUGH, 1ST MARCH, 1939

Mr. H. V. Field: The paper illustrates that armature reaction is not always to be regarded as a necessary evil. In the metadyne it is put to good use, in a manner somewhat similar to that employed in the Winter–Eichberg–Latour motor used for a.c. traction work. The necessary subdivision of the main poles in order to provide gaps for the extra pair of interpoles for the secondary brush-pair will lead to a low ratio of effective pole arc to pole pitch as compared with a normal d.c. machine. Also, the primary and secondary fluxes are subtractive in two polar projections and additive in the other pair; the former will give low flux values over half the armature surface, whilst in regard to the latter, magnetic saturation will limit the possible maximum flux. The effect of the above-mentioned factors will be to give average specific magnetic loadings of from 40 % to 50 % of the normal values for d.c. machines, with a corresponding increase in frame size and weight. Similarly we get subtractive effects of armature currents in two quadrants of the armature, and additive effects in the other two. This latter effect will considerably increase the armature heating and loss, and the machine would appear to be inferior in this respect as compared with a rotary convertor, to which it is somewhat analogous. This factor also will increase the frame size and weight. Satisfactory commutation seems probable, but careful adjustment of interpole excitation would appear to be necessary in order to avoid interference with normal machine characteristics.

The machine must presumably always work with the secondary circuit closed, as an open circuit would be equivalent to loss of field on a normal d.c. machine, with consequent loss of back e.m.f. The secondary output voltage varies from zero at no load to a value approaching the primary input voltage at full load. What percentage of input voltage is obtainable in the latter case? Are any special voltage-limits found to exist with this machine due to commutation? Voltages greater than the input voltage could be obtained if necessary by putting on an additional armature winding coupled to a separate commutator handling the secondary currents, instead of using the primary winding for the purpose, as in the binary convertor. Has this possibility been considered? It might offer advantages for special purposes. Has the operation of the machine on alternating current been considered, and, if so, are its characteristics similar?

There are many drives for which the metadyne appears to be very suitable, such as trolley-buses, cranes, winches, and capstans. The ease of reversal, coupled with effective regeneration, appear to offer advantages when applied to reversing rolling mills as an alternative to the usual Ward–Leonard system with flywheel equalizers; the authors' comments on this would be appreciated.

Arc welders and arc lamps are preferably operated at constant current, but presumably the necessity of maintaining a closed secondary circuit would rule this application out.

For cranes and similar work, comparisons with the Austin system of controlled series machines would be appreciated.

Can the author quote any energy-consumption figures showing the saving brought about by metadyne control as compared with series-parallel control, due to reduction in starting losses and use of regeneration, on typical services of the London Passenger Transport Board?

Would metadyne control be used for main-line electrification, where starting losses are relatively unimportant? The metadyne convertor used with the " 8 " connection must handle one half of the total input to the controlled motors, so that its size, weight, and cost must be appreciable, particularly in view of my earlier comments regarding magnetic loading and heating; and it seems doubtful whether the other advantages to be gained would outweigh such factors as these.

Mr. W. R. Shepherd: Mr. Field raised the interesting question of the application of the metadyne to large rolling-mill drives, and I should be glad if the authors would deal with this aspect more fully in their reply. It would be interesting to know whether the metadyne application of field-forcing is calculated to bring about improvements in the reversing times of large mill motors.

Perhaps the authors would also give some idea of the difference between the capital costs of a metadyne traction motor of, say, 50 h.p., with its simple control gear, and a standard d.c. motor with contactor gear.

Whilst the subsequent running costs may be low, and other advantages may accrue to a user of a metadyne traction-motor-driven vehicle, a high initial cost would retard the use of the metadyne by manufacturers of traction vehicles who suffer competition.

Would the metadyne have a useful application in the control of large booster fan drives of, say, 200 h.p., having a 4 : 1 speed range; and, if so, what form would the metadyne circuit take? Also, how would the losses over the speed range compare with those of the other methods of obtaining speed control, namely a separate motor-generator set in the case of d.c. fan motors, rotor-circuit resistance control in the case of a.c. fan motors, hydraulic couplings with variable slip, and pole-changing devices?

Is there any application of the metadyne generator to the control of small d.c. screw-down motors on sheet mills, where the distance travelled in between passes is very short, and where the motors travel upwards at, say, twice the speed of downward travel? If so, what would be the effect on the circuit if the rolls jammed at the limit of the downward travel?

[The authors' reply to this discussion will be found on page 394.]

NORTH-WESTERN CENTRE, AT MANCHESTER, 28TH MARCH, 1939

Mr. J. S. Peck: Some 10 years ago Prof. Pestarini visited us at Trafford Park and tried to get us interested in his metadyne patents. He was very enthusiastic, and confident of the many advantages of the metadyne system. I listened carefully to what Prof. Pestarini had to say, and eventually turned him over to Mr. Fletcher, to whom he transmitted at least some of his enthusiasm. Had it not been for Mr. Fletcher's enthusiasm, we should never have taken up and carried through the development of this machine. He and his associates have brought the development of the metadyne generator to a very successful conclusion, for certain classes of traction work. There are also special classes of industrial work where the metadyne appears to meet the requirements more completely and with greater ease than any other device of the kind that we know of.

Mr. T. Ferguson: I have always believed that of the various rotating convertor or booster systems invented for accelerating trains and braking them by regeneration, the metadyne was undoubtedly the best.

The authors hardly do justice to themselves or to their colleagues at Trafford Park when in the opening lines of their paper they attribute the development of the metadyne system entirely to Prof. Pestarini. A great amount of the development and experimental work was done at Sheffield under Mr. Fletcher's supervision, and the equipment for the control and protection of the metadyne was designed at Trafford Park.

The arrangement shown in Fig. 8 introduces many problems in regard to the control and protection of the metadyne, but great ingenuity has been exercised in solving them. The authors also appear to have overcome all the difficulties in connection with commutation on a machine which is constantly changing its function, either supplying the motor from the line or supplying the line from the motor, both processes involving separate "entries."

The authors state that a saving of 28 % to 30 % in energy was shown by a metadyne shunting locomotive on the Paris–Orléans Railway, as compared with the same locomotive before conversion to the metadyne system. I cannot accept their suggestion that this saving was entirely due to the elimination of rheostatic losses, unless the original locomotive was totally unsuited to shunting duties. The authors are very well aware that the losses in rotating machinery of the nature of a metadyne or convertor are still very considerable when it is supplying large currents at low voltages during starting; and by choosing particular conditions for comparison, one system or another will be made to show up to the better advantage. For example, under certain conditions of acceleration the total efficiency of a train acceleration movement may be higher for an ordinary equipment than for a metadyne equipment.

Mr. E. P. Hill: The term "metadyne" is defined in the paper as including various forms of dynamo having additional brush-arms intermediate between the usual brush-arms, the m.m.f. of the armature providing the principal excitation. There have been for over 30 years forms of dynamo conforming with the above description, and the principle upon which, for example, the Rosenberg dynamo operates is closely related to that of the machine described in the paper, so that an appreciation of the method of operation of the Rosenberg dynamo is of assistance in studying the further development of the metadyne. The existence of armature reaction in an ordinary d.c. generator or motor, while appreciated in the design of the machine, has no significance to a user. Commutating poles and compensating windings as fitted to modern machines render the brush position fixed at all loads, and the main field of the machine is usually accepted as that passing through the yoke and main poles and directly controlled by the field coils.

In the Rosenberg dynamo, however, the armature-reaction field at right angles to the initial flux is deliberately encouraged by the shape of the pole arc, and the normal brushes are short-circuited, producing a heavy cross field in which the armature conductors rotate.

The currents flowing in the armature conductors in connection with the intermediate brushes produce a further flux at an angle of 90°, i.e. in a direction exactly opposite to that of the initial flux. There is thus a limiting action to the current in the external circuit, producing a constant-current machine independent of speed within certain limits. It will be clear that the cross field, which in the Rosenberg dynamo is produced by short-circuiting the normal brushes in the small initial field, can be produced by supplying the armature with current from an external source as is done in the metadyne, and this leads to the production of Φ_1, which generates V_2. The introduction of the primary variator winding and other developments of the metadyne then follows.

The Rosenberg dynamo was a 2-pole machine with a gap in the centre of the pole to give space to commutate the intermediate brushes. The metadyne splits each pole into two parts, so that commutating poles can be fitted both in the normal position and to commutate the intermediate brushes.

The application of the metadyne principle to other spheres than traction appears quite possible. The high standard of commutation provided by heavy direct-current machinery to-day, resulting from care in design to ensure that all sources of unbalanced m.m.f.'s are avoided, would suggest that very careful design and adjustment will be required if the metadyne is to obtain a similar performance.

Mr. R. Brooks: In the early days of the development of the metadyne I was solemnly told—not by the authors—that here was a new device which would render control gear entirely unnecessary. It has since been proved that the adoption of the metadyne results, on traction equipments, in the elimination of the main resistances and their associated switchgear, and of the energy loss to which they give rise. At the same time this is not a clear gain, because there are other functions which have to be performed, necessitating additional apparatus. Against the saving in the rheostatic losses must be put the appreciable losses in the machines themselves; nevertheless, the advantage lies with the metadyne equipment, at least so far as the amount of contactor and similar gear is concerned.

These are, however, secondary considerations, and it is on a broader basis that the metadyne must find its justification. The fact that we have in London a great traction system employing the metadyne in commercial service very satisfactorily, is sufficient evidence that many of the difficulties have been overcome. It is evident from the paper that all the characteristics of the particular service must be considered to find out whether there is economic justification for the extra cost and weight necessarily involved in the metadyne equipment.

In suburban areas the metadyne has hitherto found its principal application. It is a matter of common knowledge that, year by year, higher, smoother, and more sustained acceleration is being demanded; and the endeavour to meet that demand has given rise to a number of new schemes, all of which have aimed, from the control point of view, at eliminating the notching peaks, in order to be able to utilize to the full the adhesion which is available, and to approximate to the smooth curve referred to in the paper. Some of these schemes—for example, the multi-notch types of equipment—give a very close approximation to the result aimed at, but the metadyne definitely achieves it by virtue of its inherent characteristics.

Mr. G. R. Higgs: During the past winter, transport suffered rather badly from snow and ice, and the electric railways of London were no exception. Many trains were delayed through ice formation on the conductor rail, and this occurred to trains of the ordinary type which were fitted with power train lines throughout. It would be interesting to know why in the case of the metadyne trains, which are not so fitted, practically no delay was experienced.

Mr. F. J. Pepworth: I wish to mention a rather interesting characteristic of the metadyne which was not obvious from the authors' demonstration, namely that the secondary current of the metadyne (I_2) varies inversely with the speed.

We attempted to apply this characteristic to the following problem. It was required that the voltage of three exciters, directly coupled to a large winder set, should remain approximately constant irrespective of a $\pm$ 20 % speed variation. It was proposed to connect the three fields of the exciters in series with a metadyne exciter which was also to be mounted on the same shaft. If the saturation curve of the secondary flux path of the metadyne had been designed to have the same shape as the saturation curves of the exciters, their voltages would have been maintained constant. As there was no d.c. supply available, it would have been necessary to have a battery floating across the primary of the metadyne, to supply the primary controlling voltage. The scheme was rejected on account of the excessive length of the main set, the use of batteries, and the disinclination to use an untried product. In its place were used separate turbine-driven generators costing a few thousand pounds more.

Mr. W. E. Swale: In their demonstration the authors indicated the possibilities of industrial applications; when I saw the extraordinary way in which the demonstration disc started, stopped, and reversed, as if controlled by a magic wand, it struck me that this is just the sort of control that is wanted on the drum-shaft of an electric winder. Will the authors discuss in their reply the application of the metadyne to the control of large winders?

In what respects are the qualities of the metadyne superior to those of the old-time Ward–Leonard system? This at least has the advantage of being a little easier for the power supply engineer to understand.

Mr. T. W. Ross: When I first came into contact with the metadyne it occurred to me that its characteristics resembled those of an ordinary current-transformer, and this analogy assisted me to visualize the principles of this method of control. Perhaps the authors will enlarge on this analogy, as it may assist others to understand the metadyne.

Mr. D. B. Hoseason: Most electrical drives can be placed in one of three groups. First, there is the normal constant-speed duty, for which the alternating-current squirrel-cage motor is the ideal solution; secondly, there is variable-speed duty such as the driving of a fan, in which, although variable speed may be desirable, the machine is expected to run for long periods at some fixed speed; thirdly, there is the variable-speed motor from which is required manipulative speed variation. If we are to look for applications of the metadyne, we shall find them principally in the manipulative speed-control group, with such typical examples as the rolling mill, the colliery winder, suburban railway electrification, elevators, and sundry others.

The problem of commutation, by no means a simple one on straightforward d.c. generators and motors, is even more involved on a.c. commutator motors. The commutation of metadynes bristles with complications, but has one very important advantage: we know from experience that machines which accelerate and decelerate frequently under varying load conditions do not, in actual service, give the trouble with commutation that may occur on a similar machine with constant speed and steady load. Even when there is only a little sparking on a steadily running motor, in due course the commutation may deteriorate until finally the machine has to be taken out of service. With motors on manipulative duty, however, users need not be alarmed if commutation is not invariably sparkless.

I presume that commutating poles are provided on the metadyne for both sets of brushes. It is a feature of constant-current systems that the voltage must change rapidly. Does this mean that the field system of the metadyne should be laminated? Otherwise, is not the flux change delayed by eddy currents when a solid yoke is employed? How does the output coefficient of the straightforward metadyne generator compare with that of the normal d.c. generator, given similar conditions?

Mr. George Barnard (Sale): Have the authors seriously compared the suitability of the metadyne system with that of a Ward–Leonard set for a colliery winder? The metadyne, being a d.c. system, cannot of course be compared with the simple straightforward geared a.c. winding equipment, but for large outputs the problem is usually centred around the exceptionally high peak currents which are generated when the winder is started from rest; and if we can get rid of these peak currents, we can do without the Ilgner flywheel. As the necessary starting torque can be obtained by the metadyne without a high starting current, it may be an

economic proposition to use the metadyne despite its high cost, as this may not be much higher than that of the Ward–Leonard–Ilgner set; there would also be the advantage of less disturbance in the connected network.

Mr. R. Gray: It appears that in the battery third-rail locomotive described by the authors there is no provision for recharging the battery whilst the locomotive is actually running on third-rail power. This restricts the charging to such times only as when the locomotive is standing idle on third-rail track, and may prove to be a considerable handicap in service by reducing the possible running hours. The work capacity of the locomotive would be increased if charging could take place at any time, whether the locomotive was standing or running, on third-rail power. Could the authors tell us whether there is serious difficulty in making charging arrangements on these lines with metadyne equipment?

My second point refers to the Diesel-electric-battery locomotives described at the end of the paper. Is it true, as appears from the description, that the full output of the engine through the metadyne is automatically pumped into the battery whenever power to the wheels is cut off? It would seem too that all surplus engine power, when the driving load is light, must also be absorbed by the battery.

Such a system takes no account of battery requirements, and if there were sufficient power to keep the battery charged up during a day when loads were heavy, serious overcharging would be likely on days when loads were light. Battery input and output should balance automatically if long battery life is to be obtained. This balance can be ensured easily with a compound-wound generator by arranging for a drooping characteristic of suitable shape: the current supplied to the battery during charging periods will then be heavy or light according to the magnitude of the battery back-e.m.f., which in turn depends on the state of charge. The metadyne, with its constant-current output, does not seem to be ideal for this particular application, and it would be interesting to have the authors' comments on the difficulty.

Mr. R. S. Blackledge (*communicated*): One of the most interesting characteristics of the metadyne is that which would be exhibited during regenerative braking. The current returned to the line would decrease gradually with the speed of the train until the voltage generated by the motors was just sufficient to balance the secondary-circuit resistance drop—when the ideal line current would be zero—and then the flux due to the primary current would build up in the (arbitrary) positive direction; a motoring current in the secondary circuit would be the consequence, and since the motor armatures are reversed for braking, the torque produced by that motoring current would sustain the braking.

In the current curve shown in Fig. 20 one would expect to find, therefore, a small positive current at the end of the braking period; but as the current curve terminates at zero before the velocity becomes zero, it would appear that steps are taken to prevent the second reversal of current, which, if sustained after standstill had been attained, would tend to start the train in the reverse direction.

Would the authors advocate field shunting with metadyne-controlled equipment, or do they consider that the size of the motors should be reduced and the equivalent full-field speed obtained by a suitable metadyne characteristic?

One of the advantages claimed for the metadyne is a reduction in energy consumption, and in this connection it would be interesting to know whether the energy regenerated during braking is credited to the train. Bearing in mind that special resistances have been fitted in order to absorb this energy, it would be an extremely optimistic procedure to credit the train with its recuperation. Clearly, these resistances will not be used in all cases, but I find it difficult to understand how any appreciable reduction in energy consumption can be achieved unless such credit has been assumed.

A set of tests on which I have had occasion to do much calculation is that relating to the electrification of the Manchester–Bury line of the former Lancashire and Yorkshire Railway.* I should be obliged if the authors would indicate the approximate reduction in energy consumption that they would anticipate on the Whitefield–Prestwich run,† if metadyne control were fitted. This section does not favour the metadyne system, so that any saving would be a useful demonstration of its characteristics in this respect.

Referring now to the constructional details of the machine, I should like to be quite sure that I have interpreted the paper correctly. On each of the main polar projections there would appear to be three coils, namely the variator, regulator, and stability windings; the interpoles, when fitted, will be symmetrically spaced but in dissimilar pairs.

In the schematic diagrams of Figs. 17 and 19, interpoles are not shown; I would ask whether it has been found unnecessary to fit them on the equipments of the London Passenger Transport Board.

In conclusion, it would appear that the metadyne has a promising future in the industrial field, particularly in those cases where the attainment of a specified performance has priority over cost, as indeed it always should have.

[The authors' reply to this discussion will be found on page 394.]

* G. Hughes: *Minutes of Proceedings of the Institution of Civil Engineers*, 1921, vol. 208, p. 196.
† *Ibid.*, p. 218.

THE AUTHORS' REPLY TO THE DISCUSSIONS AT LONDON, NEWCASTLE, MIDDLESBROUGH, AND MANCHESTER

Messrs. G. H. Fletcher and **A. Tustin** (*in reply*): In the discussion of the paper similar questions were in many cases asked at the various Local Centres, and it will be convenient to reply to them together. For this purpose we have grouped the replies under the following headings: (*a*) Questions relating to the design and performance of the metadyne. (*b*) Questions relating to the control system. (*c*) Questions relating to operation. (*d*) Other matters.

(*a*) *Questions relating to the Design and Performance of the metadyne.*

Metadyne for L.P.T.B. trains.—A considerable number of questions asked will be answered by Figs. C and D, which give the characteristics of the metadyne Type MD53 during motoring and regeneration respectively. It will be seen that the efficiency of the metadyne reaches 90 %. The form of the variation of motor torque and line current shows how the acceleration and retardation commence and finish in a gradual manner and how the current drawn from the line is small during the first part of the accelerating period, though full torque is being developed.

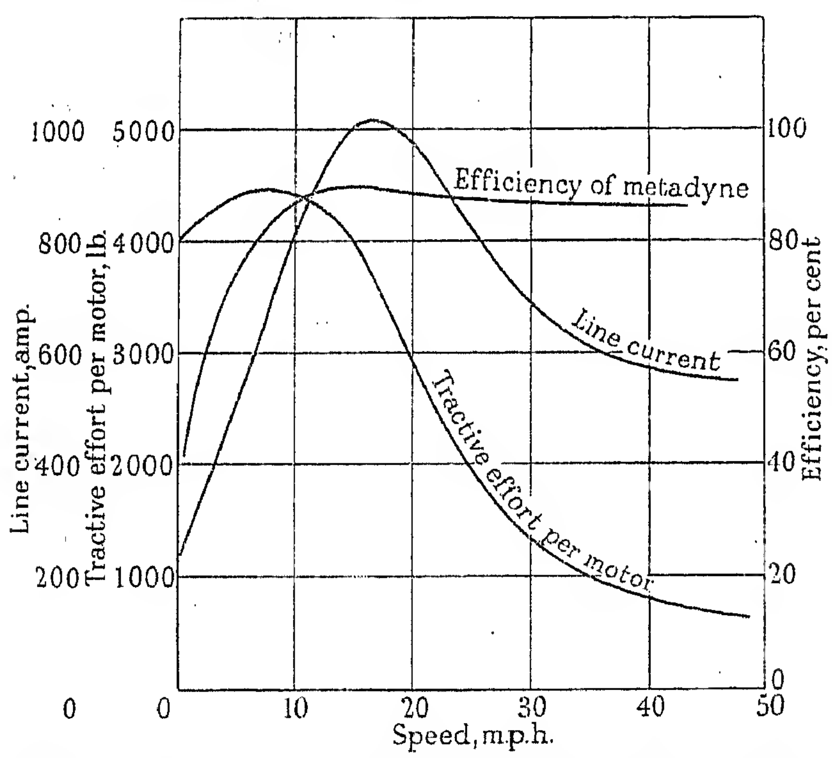

Fig. C.—Performance of metadyne MD53 with four traction motors. Motoring, 3rd notch. Line voltage, 600 volts.

The power of the motors controlled by each metadyne is 640 h.p. at the 1-hour rating. The power required to keep the metadyne running during coasting is 11 h.p., or 1·7 % of the power of the motors controlled.

Number of poles.—The number of polar projections used on the metadyne applied to the L.P.T.B. is four; in other words it is a single-cycle metadyne. Selection of the number of cycles is made on similar grounds to that determining the choice of the number of poles in an ordinary dynamo. A consideration in this case was the restricted overall height, due to the mounting of the machine under the floor of the coach. It is probable that a two-cycle design, i.e. one with eight polar projections, would give a somewhat lighter machine on account of the reduced thickness of yoke and depth of core required; but it would be more difficult to secure the necessary small diameter, and the large number of brush arms would probably result in an increase in cost.

Number of field windings.—Comment was made on the considerable number of field windings used in the metadyne. On the metadyne for the sample train MD53A there were 5 coil-sections on each main polar projection, and two on each interpole. On the service design this was reduced to four on each main pole and one on each interpole. Fortunately, developments that have been completed since the paper was written have enabled this number to be reduced to three (or sometimes only two) on each main pole, and one on each interpole, so that the stator is now scarcely more complicated than that of an ordinary compound generator—even in the case of an eight-connected machine with stabilizing windings. The large number of separate sections originally used was due to the splitting of each of the stabilizing windings and of the interpole windings of both the primary and the secondary circuits equally between the two loops of the "eight" circuit, as this was found to result in more perfect and constant equality between the currents of the two loops, and to prevent any tendency of the current to swing from one loop to the other.

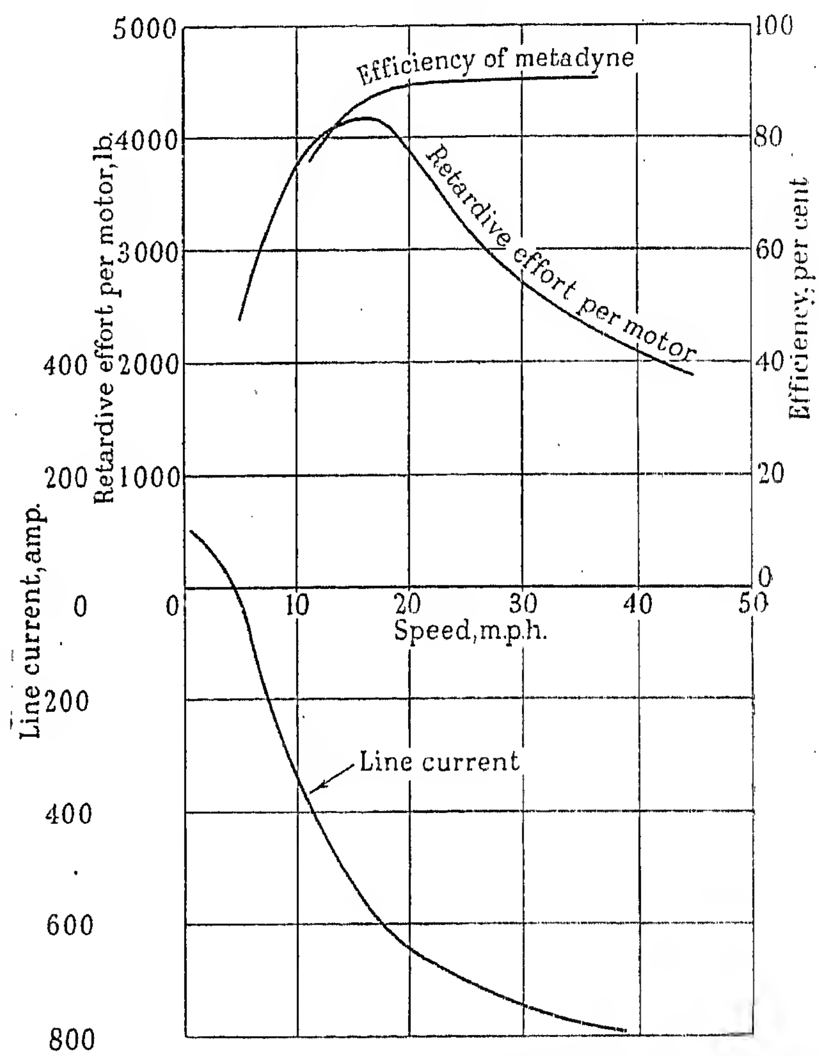

Fig. D.—Performance of metadyne MD53 with four traction motors. Regenerating, 2nd notch. Line voltage, 700 volts.

It has now been found (British Patent No. 496494—1937) that by arranging the sequence of connection of the interpole coils in correct relationship with the chording of the armature winding a powerful equalizing effect may be obtained on the current in the two loops, and this has made unnecessary the previous complication of the stator windings.

Ventilation.—The metadyne is self-ventilated, but the ventilating air is drawn from the interior of the coach where it contributes to good ventilation. At the same time the metadyne is kept comparatively free from dust.

Weight.—The weight of the metadyne set, complete with its regulator motor and exciter, is 3·7 tons. The weight of the corresponding control equipments complete, per unit of two coaches (i.e. the control gear associated with each metadyne), is 1·2 tons for the three switch groups, all resistances, and the metadyne joint box, but excluding the master controller, cabling, and collecting gear.

It is somewhat difficult to give an exact comparison of the weight of the switchgear required on a metadyne equipment with that required for a corresponding rheostatic equipment, since of course it is impossible to say when equipments of such different duties "correspond" in size. As an indication, however, we may compare the metadyne equipments on the L.P.T.B. with a typical modern rheostatic equipment of a similar number of motors and a similar power. On this basis, including corresponding items, we find that the rheostatic control equipment weighs 1·35 tons as compared with 1·2 tons for the control equipment associated with the metadyne. Both these figures exclude the weights of items common to both schemes, such as the master controller, cabling, and collecting gear.

Design limitations in metadynes.—There are no special limitations in the design of metadynes which do not apply to the ordinary dynamo. The reactance voltage of the MD53 metadyne is 2·8 volts per bar. This is comparable with the value which is usual in the design of railway motors, and with this value no special commutation difficulties have been found. The winding is chorded by $\frac{1}{2}$-slot less one commutator bar. The peripheral speed of the armature is 10 200 ft. per min., and as the machine always rotates in one direction highly efficient self-ventilation may be arranged.

The ohmic loss in the armature winding of a metadyne is the sum of the losses calculated for the separate primary and secondary currents, since they are at right angles, and not from the square of the sum of these currents as would be the case if they were merely superimposed. With the eight-connection the mean square primary current is only about 50 % of the mean square output current, so that the total copper loss is less than might be imagined.

Temperature variation of armature winding.—An interesting point was raised by Mr. Fairburn regarding the possible effect on the life of the windings of heating and cooling during spells of motoring, coasting, and regenerating successively. As Mr. Graff-Baker pointed out, a greater frequency of spells of heating is likely to make the range of temperature variation less, and the actual variations of temperature are in any case very small. We have calculated the variation in temperature over a cycle of motoring, coasting, and regenerating, and find that the range of variation is $\pm$ 1·3 deg. C. from the mean temperature. No extra deterioration of the winding can therefore possibly be caused by the expansion and contraction due to the additional regeneration period.

Commutation.—The comments of a number of speakers show that even among designers there is a widespread impression that some special difficulty is to be expected in securing good commutation in metadynes that is not met with in ordinary dynamos. This impression is corrected by a little consideration of the facts. It is true that in metadynes the current in a coil as the coil passes a brush position does not always completely reverse from a positive to an equal negative value: only part of it reverses, while the part corresponding to the current of the other set of brushes of course does not change. The amount of current which reverses is that corresponding to the current in the brush arms which the coil is passing, and interpoles are provided, excited by this current, so that the compensation of the reactance voltage is carried out perfectly normally, and each circuit (i.e. the primary and the secondary circuits) is considered entirely separately so far as concerns the design of the respective interpoles.

The only abnormality during commutation is the presence in the conductors that are commutating of a constant-current component from the other of the two circuits. As this component is constant it cannot affect the reactance voltage. Its only effect is to give a slight constant cross-magnetization in the commutating zone. If it were necessary, this cross-magnetization could quite easily be compensated by a local compensating winding of very small ampere-turn value, arranged in the interpole face. In practice it is not found necessary to introduce any such local compensation of the ampere-turns from the other circuit, and no difficulties have been found to exist on account of the slight cross-magnetization. Fig. E may make this point clear: it shows the actual disposition of currents under the interpoles for the case in which $I_2 = \frac{1}{2}I_1$. At the bottom of Fig. E is shown the actual disposition of currents in the armature, and the m.m.f. and flux distribution due to the resultant armature-reaction. Above are shown the corresponding component distributions of current, m.m.f., and flux, due to the secondary and primary currents separately. In any commutating zone, e.g. that under interpole No. 1, it is clear that the commutation of the corresponding current (in this case the primary current) is perfectly normal, as shown at A and A′, except for the presence of the very small cross-magnetization due to the secondary current, shown at B and B′.

The average value of this flux, and the value at the centre of the commutating zone, are both zero, and actual values are very small. The resultant m.m.f. and flux distributions are shown in the lower diagram, and it will be seen that the flux in the commutating zone is practically the same as if the cross-magnetization did not exist.

The yokes of the metadynes for traction are not laminated to speed up flux-changes. This is done, however, in certain cases such as metadyne exciters, where extremely rapid response is the object of the use of the metadyne, and where the lag in the yoke flux might otherwise be a limitation.

Rating.—The rating of a metadyne cannot be fully expressed in terms of the continuous output that it will give at full output voltage, since for this particular condition the primary current is a maximum and the flux distribution is the least favourable, so that a metadyne fully suited to control given motors on a service schedule would usually be much smaller than the metadyne that would be required to maintain the motors indefinitely at their usual continuous rating. We have therefore made no attempt to establish an equivalent continuous rating for metadynes for traction; but we design the machine so that it will perform a given cycle of acceleration, coasting, and retardation, continuously, and we verify this rating by actually maintaining the cycle of operations for the required time with the motors driving a flywheel equivalent to the inertia of the train unit.

Comparison with motor-generator booster schemes.—It is obvious that characteristics similar to those of a metadyne could be obtained by the use of booster arrangements, as mentioned by Mr. Charnley and others. In the equivalent two-machine arrangement, however, it is obvious that there is considerable duplication of both electrical and mechanical material. A still more important difference is that the stability of such machines with respect to voltage interruptions, surges, or short-circuits is in general very inferior to that of metadynes. This is because the metadyne depends for its excitation on armature reaction, and the excitation adjusts itself to changes in the voltage distribution with great rapidity. In an equivalent motor-generator or motor-booster arrangement the response of the flux is necessarily less direct, and larger current surges would be expected. The difficulties of connecting large compound-wound machines to traction circuits are well known.

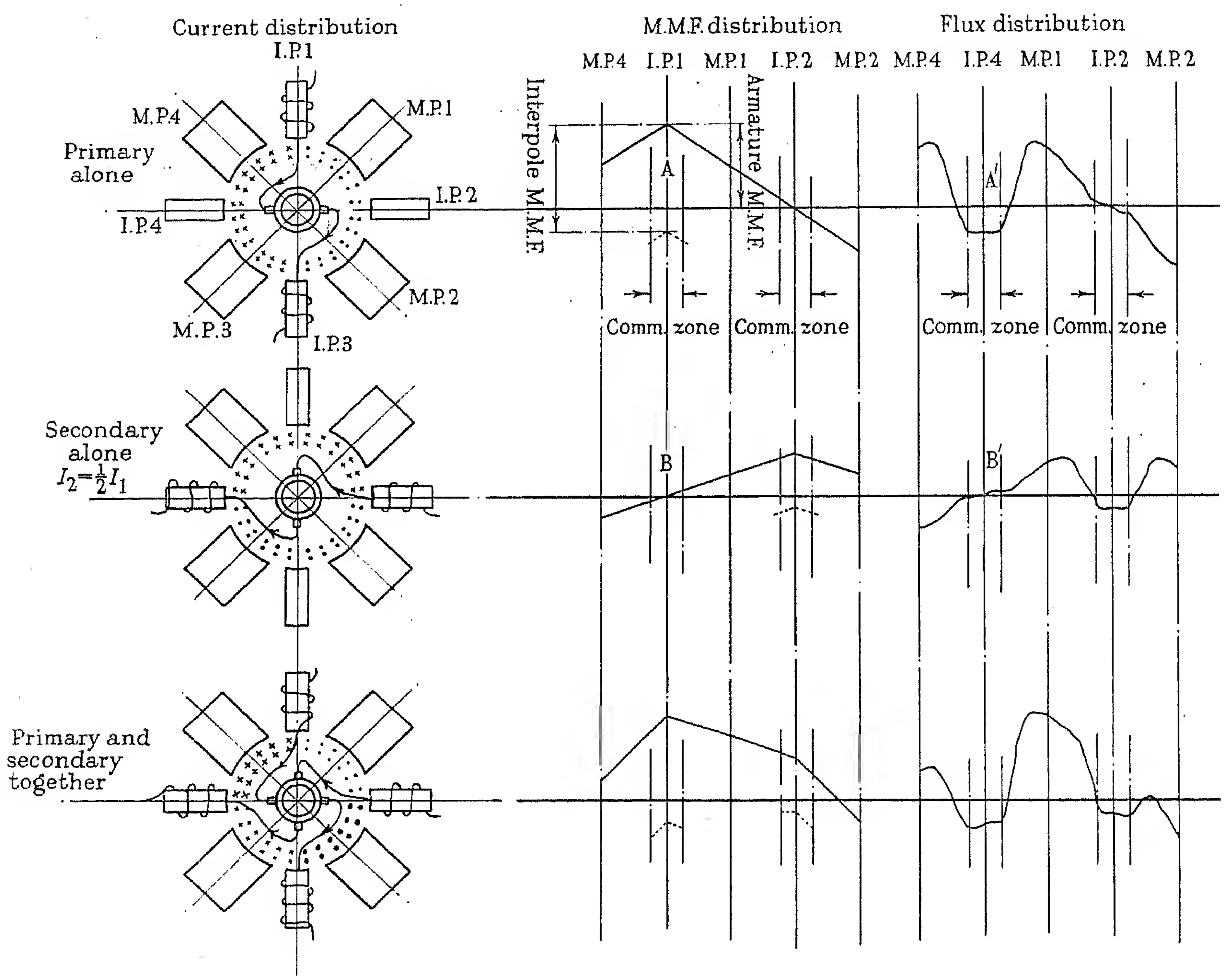

Fig. E.—Diagram showing commutation conditions in metadynes.

Use of separately excited motors.—Several of those who took part in the discussion asked why the motors are compound-wound, and whether part of the speed control is by field variation. It is a remarkable fact, which has been demonstrated experimentally, that it is possible to regenerate on to a constant-voltage line through a metadyne from series motors, the stable constant-current property of the metadyne overriding the well-known instability of the series generators alone. If regeneration is required, however, there are advantages in compound excitation, as it is found that protection in the case of fault conditions is more easily obtained. Field control is not primarily used to obtain speed variation. In an essentially variable-voltage system there is

not the same necessity for this as in constant-voltage systems. It is convenient, however, to supply the field from the same exciter as supplies the variator excitation. This maintains a field strength which tends to vary in the same way as the armature current varies, so that field distortion is minimized with minimum losses, and the flux variation also makes a contribution to the required variations in torque.

(b) *Questions relating to the Control System.*

Amount of switchgear required.—Several speakers remarked on the fact that though the amount of switchgear required is clearly less than with the rheostatic equipment, the number of contactors and other items of control gear is considerable. This observation is to some extent correct, and a comparison of control-gear weights has been given above. It should be pointed out, however, that a certain amount of this switchgear is not wholly inherent in the metadyne control, but has been added to meet the operating conditions on the L.P.T.B. system. The chief of these are as follows:—

(i) The rate of retardation required, namely 3 m.p.h. per sec., is too great to be obtained by retarding only the number of motored axles used on these coaches. This involves a special interlinking of regenerative and air braking, with the corresponding complications of the equipment, which would be avoided if a larger number of smaller motors were used.

(ii) As the substations have not yet been fitted with special equipment for accepting regenerative energy, each train unit must carry a loading resistance together with the necessary switchgear to insert it in the event of the line being unreceptive.

(iii) The operating conditions require two separate balancing characteristics: one for short runs, giving a balancing speed of 35 m.p.h., and the other for longer runs, with a balancing speed of 45 m.p.h., the accelerations up to 20 m.p.h. being the same in both cases. This requirement also slightly increases the complication of the switchgear.

(iv) It was considered advisable to provide separate reversers for the motors on the "A" car as distinct from those of the "B" car of the 2-coach unit. This accounts for the use of twice the normal number of reversers. It avoids a certain amount of cabling and power jumpers, but is not otherwise essential.

Mr. Brooks confirms the view of Mr. Graff-Baker that while on paper the control equipment associated with the metadyne appears to be somewhat complex, nevertheless the majority of the circuits and contacts deal with light currents, and it is expected that the maintenance of the control gear should be considerably less than that of standard equipment.

We should like to take this opportunity of expressing our appreciation of the neat solutions devised by Mr. Brooks and his associates for many of the problems which arose in connection with the development of the metadyne system.

Maintenance.—With regard to the maintenance of the control equipment, it must be noted that there are only five switches dealing with the main power current, the remaining switches being of small capacity and requiring practically no maintenance. It was at first found that the maintenance of the arc chutes on the main switches was rather considerable, because they opened large currents both when motoring and when generating. A recent modification, however, has enabled the current to be reduced before the switches open, by opening the field circuits first. With this arrangement the erosion of the arc chutes compares very favourably with that in any ordinary equipment.

Number of train wires.—The number of train wires required for parallel operation of any number of train units is nine, as compared with eight for the corresponding rheostatic equipments without regeneration.

Effect of open-circuits.—Protection is provided to meet the possibility of open-circuiting of the line or supply during regeneration by the automatic connection of the loading resistance under control of a voltage relay. In reply to Mr. Field, opening of a secondary circuit will cause the circuit-breaker in the primary circuit to open on overload.

It was quite correctly pointed out by Mr. Blackledge that at the end of regenerative braking a point would be reached at low speed at which the regenerated energy would become less than the machine losses, and the current in the line would reverse. The reason why this effect does not appear on the records is that the reduction of current is made to operate a low-current relay which cuts off the metadyne at the point where it ceases to be useful and causes the application of the air brakes to complete the stop.

(c) *Questions relating to Operation.*

Mr. Fairburn asked whether a limiting length of run could be given for which the use of the metadyne ceased to be economical. Such a limit cannot be stated at the present time. The possibility must, for example, be considered of designing equipments such that the metadyne is only used for accelerating and braking, the motors being connected directly to the line and the metadyne currents reduced to zero as soon as the voltage is brought up to the line value. Such an arrangement would enable a smaller metadyne to be used when the lengths of run are longer, which would to some extent offset the smaller relative importance of the saving of brake shoes and of energy. As such possibilities have not yet been fully explored it is not possible to say what will prove to be the maximum economical length of run.

Effect of variation of line voltage.—It was suggested that undesirable variations of tractive effort might occur owing to the effect on the motor current of variation in the line voltage. It is true that on the elementary form of metadyne without stator windings the secondary current is proportional to the primary voltage, and as the metadyne becomes saturated the rise of current increases still more quickly, if the speed is constant. If the speed rises with the line voltage (which depends on the design of the "regulator dynamo") the rise of current will be correspondingly reduced.

In the metadyne with variator windings, as actually used, the variation of output current with line voltage is less. The current may be regarded as the sum of two parts. Firstly, the "magnetizing current," corresponding to the current of the metadyne without stator windings; and secondly, the current produced by the variator

excitation. The latter current is dependent only on the exciter voltage, and not on the line voltage, and as this component current is much greater than the magnetizing component the total current is not so greatly dependent on the line voltage as would otherwise be the case. On the MD53 metadyne, the resultant current increases only about half as much as it would if directly proportional. It must, however, be pointed out that on the normal series motor, when working with any degree of saturation, the increase in current due to a rise of line voltage is enormously more than in direct proportion to the voltage. In this respect, therefore, the metadyne has a marked advantage, and may be still further improved if this is found desirable.

Use of more motored axles.—It is quite true, as Mr. Fairburn suggested, that full advantage of the metadyne could only be taken by motoring more axles. No doubt in this case a rheostatic equipment could also give the required acceleration, but the metadyne can give the smoothness of operation which becomes more important at high acceleration, and the completely regenerative braking which is also possible with a sufficient number of motored axles. For these reasons we believe that a combination of metadyne control with an increased proportion of motored axles is a very desirable and probable line of future development.

Reception of regenerated energy.—The problem of making rectifier substations capable of accepting regenerated energy may be solved in various ways, all of which require some additional apparatus. It is only rarely that such regenerated energy is returned from a traction system with heavy traffic, since the trains that are motoring at any moment almost always absorb more energy than is being regenerated. There is therefore no need to cater for the return of such rare momentary surpluses; it is more economical to arrange for them to be absorbed by a short-rated resistive load, automatically switched-in on rise of voltage.

The problem has been solved in a highly satisfactory manner by a system which was recently introduced* in which the loading resistance is connected across the line by the action of an "ignitron" discharge vessel. This type of control is greatly superior to the alternative relay and contactor systems, because it is almost instantaneous in action. The resistance is effectually connected in a few thousandths of a second from the instant at which the operating voltage is first reached, so that no high voltage can occur even on the most rapid voltage-rises. Such an arrangement is of course equally applicable in the case of existing rotary-convertor substations, which on account of the design of the machines cannot readily take reversed current. The resistance is switched out as soon as the current becomes positive again. Such equipments have been in service under conditions in which as many as 40 momentary reversals of power per hour were experienced, and under such conditions they kept the maximum voltage to within 10 % of the nominal supply voltage.

Economy in service.—We are glad to learn of the systematic measurements of power consumption with and without regeneration that are promised by Mr. Graff-Baker. It is obvious that, when a number of trains are regenerating while others are taking power, there is an economy in feeder and third-rail losses that is not included in measurements made at the train. Furthermore, the voltage is better maintained. On the other hand, under some conditions part of the regenerated energy is lost in the line voltage-drop. The proposed tests will establish the balance of these factors under practical operating conditions.

Operation with ice on the rail.—It is true, as Mr. Higgs remarked, that the trains with metadyne control gave better service than trains with rheostatic control during certain unusual icebound conditions on surface sections of the lines. This peculiarity was not foreseen, and the exact explanation for it could probably only be given with assurance if recorder readings were taken on both types during such operation. Our view is that the difference is accounted for by the following facts:—

(i) A metadyne train requires a very low current for starting, since even at full torque there is no power output. The rheostatic equipment, however, requires full current, the full power at the moment of starting going into the rheostats. Thus a rail-contact resistance of a given value may prevent a rheostatic train from getting away, but scarcely alter the tractive effort on a metadyne train.

(ii) On a sudden change of contact resistance the series motor may take a considerable surge of current, causing the wheels to slip. The motors fed from metadynes, however, maintain a more constant torque, and the wheels do not slip.

(iii) Under ice conditions there are liable to be repeated interruptions and remakes of the power supply. Series motors, when their resistances are nearly completely cut out, will trip their circuit-breakers under such conditions and necessitate the return of the controller to the off position. With the metadyne, interruptions up to about 1 sec. in duration during motoring at low speed do not cause disconnection of the circuits. The voltage is maintained by the rotation of the metadyne, and there is no appreciable surge on remake. The operation continues in spite of such interruptions without attention on the part of the driver or loss of time.

Battery locomotives.—Mr. Gray asks whether the battery of the battery locomotive described could be charged during running. This cannot be done on the system described, and if it was required would necessitate either a different system or the addition of a separate battery charging set. In practice, it was not required.

In the project for Diesel-electric-battery operation described, the possibility of overcharge of the battery by excessive regeneration would of course be considered in the case of each individual design. If necessary, some form of supplementary loading resistance could be provided.

Metadyne locomotives on the Paris–Orléans Railway.—Mr. Ferguson appears to have some doubt regarding the saving of energy which was shown by the metadyne shunting locomotive on the Paris–Orléans Railway, and apparently does not consider the comparison to be favourable. We are very glad to have Mr. Bird's confirmation with regard to the actual saving effected, and we would stress the fact that the comparison is not

* See *Railway Gazette* (*Electric Railway Traction Supplement*), 1938, vol. 69, p. 664.

between the metadyne locomotive and the same locomotive before conversion, but between a converted locomotive and a different shunting locomotive with rheostatic control.

While it is true that the losses in the metadyne, when supplying large currents at low voltages during starting, are considerable, at the same time with rheostatic equipment the whole of the voltage-difference between line and motor voltage represents energy loss, and these losses may have a value higher than the normal output of the locomotive. We understand that the use of battery and 600-volt operation on the Paris–Orléans locomotives, that was provided for on the first sample, has been omitted on the later locomotives.

(d) Other Matters.

We were very interested in Mr. Macfarlane's reference to earlier machines of the same general family as the metadyne. In our reference in the paper to Prof. Pestarini as its inventor we did not intend neglect of earlier developments, but desired to acknowledge our own indebtedness to the work of Prof. Pestarini both for (so far as we know) the only systematic and complete study of such machines in all their forms, and also for such developments as stabilizing windings, the " eight " connection, the regulator circuit, and the facility for obtaining specially shaped characteristics which have made such machines practicable and economical for traction work.

The best-known of all machines which have a close resemblance to the present metadyne is, of course, the Rosenberg dynamo, and Mr. Hill has given a very clear account of the relationship of this machine to the metadyne. The machine described in the Brown-Boveri patent of 1908 mentioned by Mr. Macfarlane is also an elementary form of metadyne transformer, practically identical with the simple form which was described for purposes of exposition in the paper, but excluding the developments such as those mentioned above that have been necessary to make such a machine suitable for heavy traction.

The second form of convertor mentioned in Mr. Macfarlane's communication, which he refers to as a split-armature type, is simply a metadyne with a short-pitched winding; this is sometimes, but not usually, preferable. The machine which we used for our demonstration at The Institution was of this type. This short-pitched winding form of metadyne, as Mr. Macfarlane states, has the great disadvantage of requiring twice as much iron section in the yoke and core as the full-pitched type, or alternatively twice as many armature conductors. It is therefore much heavier for a given output, in spite of the reduced end-winding length.

Metadynes may be made with the coil pitch of various fractions of a cycle, if suitable commutating arrangements are made.*

Mr. Calverley recalled his association with one of us in developing the Thury machines many years ago. Recollection of the commutating difficulties on these machines suggests to him that there might be similar difficulties on metadynes. In the Thury machines, however, the brushes were moved underneath the main poles, and the armature reaction had to be arranged to give some sort of compensation of the main field. As already explained, the commutating conditions in metadynes are not complicated in this way, and are easily satisfied.

Dr. Rosenberg makes an interesting comparison of the metadyne with cross-field machines investigated by him so long ago as 1905. We fully appreciate the pioneer work that was done by him in this field, which produced the well-known Rosenberg dynamo to which reference has already been made.

Many questions were asked and suggestions made by Mr. Shepherd, Mr. Barnard, and others on the subject of the application of metadynes to engineering problems other than traction. It is not possible to discuss these suggestions in detail in the present reply, which deals with traction problems; but the matter may be summarized by classifying the most useful properties of the metadyne system in the following way: (i) It can produce a controlled torque, readily adjustable and either constant or automatically changing according to load or other conditions. (ii) It is not inherently suited to giving closely controlled definite speeds (except creeping speeds). (iii) It has a separate field of use on account of its extreme quickness of response (exciters, etc.).

It is our belief that the metadyne will be as useful in many other fields as it is proving itself in traction.

* J. M. Pestarini: *Revue Générale de l'Électricité*, 1930, vol. 27, pp. 355, 395; and 1930, vol. 28, pp. 227, 260, 813, 851, 900.

AN OPERATIONAL TREATMENT OF THE DESIGN OF ELECTROMAGNETIC TIME-BASE AMPLIFIERS*

By L. JOFEH, Graduate.†

(*Paper first received* 28*th June, and in revised form* 15*th December*, 1938.)

SUMMARY

The operation of electromagnetic time-base amplifiers is analysed and simple expressions are deduced from which their performance is readily predictable. The results thus obtained are discussed and the steps to be taken for the avoidance of undue distortion of the signal wave-form are indicated.

The variations in anode potential of the amplifier valve are calculated; in particular, the maximum values of anode potential excursion are found, from which the H.T. supply voltage and the degree of insulation needed may be deduced.

It is shown that much of the information required for the design of this type of amplifier may be obtained by consideration of the expression for the indicial transfer admittance.

Finally, it is pointed out that the results obtained may be applied to a modified form of amplifier by means of slight changes in notation.

CONTENTS

(1) INTRODUCTION

The advent of television, employing cathode-ray apparatus for transmission and reception, has caused attention to be directed to the design of time-bases for the deflection of the beam; electrostatic and electromagnetic time-bases have been and are being used, but as yet the theoretical side of the subject has been but sparsely treated in the literature. In view of the complexity of the problem, particularly with regard to magnetic deflection, this state of affairs is somewhat surprising; however, a few papers‡ have appeared on magnetic deflection, and a closely analogous problem occurring in one type of electrostatic time-base has also been discussed.§

It is unfortunate that in every instance the problem has been attacked by means of Fourier analysis, with the result that the expressions finally derived have been couched in such terms as to be almost uninterpretable except at the cost of an excessive amount of labour. Moreover, most of these authors have contented themselves with making arbitrary (and often quite fictitious) assumptions as to the way in which the various components of the wave are treated by the circuit. For example, the assumption most commonly made is that the fundamental and all harmonics up to some fairly high order, say the nth, are transmitted equally and without relative phase shift, but that the $(n+1)$th and all higher harmonics are completely suppressed.

To the present author the practice of resolving a wave into its components appears quite unnecessary, since there exists a method, namely that of the Heaviside

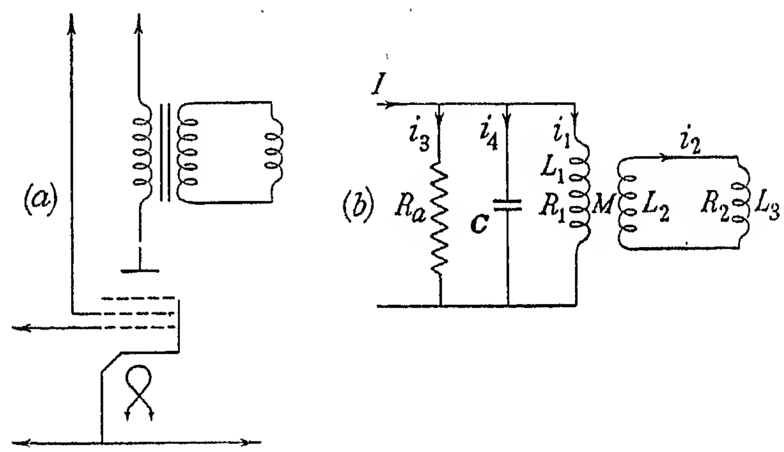

Fig. 1

(*a*) Basic circuit of output stage.
(*b*) Equivalent electrical circuit.

operational calculus, which enables one to handle the wave as a whole and which, moreover, allows one to obtain results of such simple forms that it is quite unnecessary to make any involved calculations when one wishes to ascertain the effects on the result of any of the circuit components. Unfortunately, the operational calculus does not appear to be as widely known among engineers as it undoubtedly deserves to be; accordingly, while this paper makes no pretensions to being in any way an exposition or a critique of the method, the various steps in the analysis have been explained in greater detail than might otherwise have been needed.

The type of time-base amplifier discussed in this paper is shown in Fig. 1(*a*), where saw-toothed waves derived, for example, from a blocking oscillator, are applied to the grid of the amplifier valve which feeds current to the deflector coils through a transformer.

(2) NOTATION

g = mutual conductance of valve, in amp./volt.
R_a = effective anode-slope impedance of valve, in ohms.

* The Papers Committee invite written communications, for consideration with a view to publication, on papers published in the *Journal* without being read at a meeting. Communications (except those from abroad) should reach the Secretary of The Institution not later than one month after publication of the paper to which they relate.
† A. C. Cossor, Ltd.
‡ See Bibliography, (1, 2, 3).
§ *Ibid.*, (4).

L_1, L_2 = inductances of the primary and secondary windings of the transformer, in henrys.
M = mutual inductance between these windings, in henrys.
s = ratio of primary turns to secondary turns.
R_1 = effective primary resistance of transformer, in ohms.
R_2 = resistance of secondary winding and deflector coils in series, in ohms.
L_3 = inductance of deflector coils, in henrys.
C = total stray and distributed capacitance, transferred to the primary side of the transformer, in farads.
I, i_1, i_2, i_3, i_4 = currents flowing in various parts of the circuit, as shown in Fig. 1(b), in amperes. Standing currents are neglected here. The current I is the "forced" current of the valve.
V = magnitude of change of grid-cathode potential, in volts.
$\mathbf{1}$ = Heaviside unit function.
p = operator, d/dt.

indicial transfer admittance is equal to the current i_2 flowing through the deflector coils, expressed as a function of the time elapsed since the instant $t = 0$, divided by the magnitude of the change in grid potential V. It is important to evaluate the indicial transfer admittance, which in the usual notation we designate by $A(t)$, as it completely expresses the behaviour of the circuit.

For the moment we may regard the operator p as simply a convenient method of writing d/dt, and the operator $1/p$ as $\int dt$. Then, by inspection of Fig. 1(b), we can at once write the following equations:—

$$I = i_1 + i_3 + i_4 = gV\mathbf{1} \quad . \quad . \quad . \quad . \quad (1)$$

$$R_a i_3 = \frac{1}{Cp} i_4 = (L_1 p + R_1) i_1 - Mpi_2 \quad . \quad . \quad (2)$$

$$Mpi_1 = \left\{(L_2 + L_3)p + R_2\right\} i_2 \quad . \quad . \quad . \quad . \quad (3)$$

On eliminating i_1, i_3, and i_4, between (1), (2), and (3), and putting $M^2 = L_1 L_2$, we get

$$\frac{i_2}{V} = \frac{R_a}{R_a + R_1} \cdot \frac{Mgp\mathbf{1}}{\frac{L_1 L_3 C R_a}{R_a + R_1} p^3 + \left[\frac{L_1 L_3}{R_a + R_1} + \frac{C R_a}{R_a + R_1}\left\{R_1(L_2 + L_3) + R_2 L_1\right\}\right] p^2 + \left(L_2 + L_3 + \frac{R_2 L_1 + C R_1 R_2 R_a}{R_a + R_1}\right) p + R_2}$$

or, since $R_a >> R_1$, and hence $(R_a + R_1) \simeq R_a$

$$\frac{i_2}{V} = \frac{Mg}{L_1 L_3 C} \cdot \frac{p}{p^3 + \left(\frac{1}{CR_a} + R_1 \frac{L_2 + L_3}{L_1 L_3} + \frac{R_2}{L_3}\right) p^2 + \left(\frac{L_2 + L_3}{L_1 L_3 C} + \frac{R_2}{L_3 C R_a} + \frac{R_1 R_2}{L_1 L_3}\right) p + \frac{R_2}{L_1 L_3 C}} \mathbf{1} \quad . \quad . \quad (4)$$

In the analysis the following basic assumptions will be made:—

(a) The valve is operated over the linear part of its grid-voltage/anode-current characteristic.
(b) The grid-to-anode admittance of the valve is zero.
(c) The inter-winding capacitance of the transformer is zero.
(d) The primary and secondary windings of the transformer are linked without magnetic leakage.

Conditions (a), (b), and (c), are readily satisfied, the first two by choice of a suitable valve and the provision of screening between grid and anode circuits, the third by inserting an earthed screen between the two windings on the transformer. Generally speaking, assumption (d) is not strictly justifiable since, unless the transformer is wound toroidally, there is bound to be a small amount of magnetic leakage; however, by using suitable materials and taking reasonable care with the design of the transformer, the leakage may be made very small, and its effect will be discussed later.

3(a) INDICIAL TRANSFER ADMITTANCE

The indicial transfer admittance may be defined in the following way. At some instant which we arbitrarily define as $t = 0$, let us suddenly change the grid potential by inserting some steady voltage; then, the

Equation (4) is the operational statement of the problem, and we must now interpret it as an explicit function of time. To do so we factorize the denominator or, in other words, find the roots of the equation formed by setting the denominator equal to zero. In seeking to do this, we note that positive roots are inadmissible, since they correspond to a physically unrealizable condition; therefore the roots are either all negative or else one is negative and the other two are conjugate complex roots having negative real parts. Regarding the problem from the physical aspect, the latter alternative appears the more probable, and hence we write equation (4) as

$$\frac{i_2}{V} = k \frac{p}{(p + \beta)(p + \alpha + j\omega)(p + \alpha - j\omega)} \mathbf{1} \quad . \quad (5)$$

where $$k = \frac{Mg}{L_1 L_3 C}$$

Expanding (5) into partial fractions,

$$\frac{i_2}{V} = k\left[\frac{-\beta}{(\alpha - \beta)^2 + \omega^2} \cdot \frac{1}{p + \beta} - \frac{\alpha + j\omega}{2j\omega(\alpha - \beta + j\omega)} \cdot \frac{1}{p + \alpha + j\omega} + \frac{\alpha - j\omega}{2j\omega(\alpha - \beta - j\omega)} \cdot \frac{1}{p + \alpha - j\omega}\right]\mathbf{1}$$

This equation is now in a form permitting of the immediate application of the operational formula*

$$\frac{1}{p+\lambda}1 = \frac{1}{\lambda}(1 - e^{-\lambda t})$$

On making the indicated transformation and performing some quite straightforward but slightly tedious algebra, we obtain the solution

$$A(t) = \frac{k}{(\alpha-\beta)^2+\omega^2}\left[e^{-\beta t} - e^{-\alpha t}\left(\cos\omega t + \frac{\alpha-\beta}{\omega}\sin\omega t\right)\right] \quad . \quad (6)$$

provided that ω is real and not zero. If ω is not real but is equal to $j\omega'$

$$A(t) = \frac{k}{(\alpha-\beta)^2-\omega'^2}\left[e^{-\beta t} - e^{-\alpha t}\left(\cosh\omega' t + \frac{\alpha-\beta}{\omega'}\sinh\omega' t\right)\right] \quad . \quad (7)$$

while if ω vanishes

$$A(t) = \frac{k}{(\alpha-\beta)^2}\left[e^{-\beta t} - \left\{1 + (\alpha-\beta)t\right\}e^{-\alpha t}\right] \quad . \quad (8)$$

We have now to evaluate the parameters α, β, ω, in terms of the circuit constants. Comparison of (4) and (5) shows that a direct algebraic solution will be extremely difficult in the general case. Accordingly we adopt the following procedure.

Expanding the denominator of (5) as

$$p^3 + (2\alpha+\beta)p^2 + (\alpha^2+\omega^2+2\alpha\beta)p + \beta(\alpha^2+\omega^2)$$

we set it equal to

$$p^3 + ap^2 + bp + c$$

Identifying coefficients of like powers of p, we have

$$\begin{aligned} a &= 2\alpha + \beta \\ b &= \alpha^2 + \omega^2 + 2\alpha\beta \\ c &= \beta(\alpha^2+\omega^2) \end{aligned}$$

Considerations of the physical aspect of the problem show that C can only affect the value of β to the second or higher order of small quantities, so that to a close approximation

$$\beta = \lim_{C\to 0}\left\{\frac{\sqrt{(b^2-4ac)}-b}{2a}\right\} \quad . \quad . \quad . \quad (9)$$

Knowing β, we have

$$\alpha = \frac{a-\beta}{2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (10)$$

$$\omega = \sqrt{\left[\frac{c}{\beta} - \alpha^2\right]} \quad . \quad . \quad . \quad . \quad . \quad (11)$$

If $b^2 >> 4ac$ then, approximately,

$$\left.\begin{aligned} \beta &\simeq \frac{c}{b} \\ \alpha &\simeq \frac{a}{2} \\ \omega &\simeq \sqrt{[b - \tfrac{1}{4}a^2]} \end{aligned}\right\} \quad . \quad . \quad . \quad (12)$$

* See Bibliography, (5, 6).

To obtain guidance in the rejection of small terms we substitute numerical values, and for this purpose it is convenient to consider first a "line" time-base, and then a "frame" time-base.

3(b) LINE TIME-BASE

In this instance the following values are of the right order:—

$L_1 = 6$ H; $L_2 = 60$ mH; $L_3 = 4$ mH; $C = 50\ \mu\mu$F;
$R_a = 6 \times 10^4\ \Omega$; $R_1 = 600\ \Omega$; $R_2 = 15\ \Omega$.

These values give

$$\begin{aligned} a &= \frac{1}{CR_a} + R_1\frac{L_2+L_3}{L_1L_3} + \frac{R_2}{L_3} \\ &= 3{\cdot}33 \times 10^5 + 1{\cdot}6 \times 10^3 + 3{\cdot}75 \times 10^3 \\ &\simeq \frac{1}{CR_a} \end{aligned}$$

$$\begin{aligned} b &= \frac{L_2+L_3}{L_1L_3C} + \frac{R_2}{L_3CR_a} + \frac{R_1R_2}{L_1L_3} \\ &= 5{\cdot}33 \times 10^{10} + 1{\cdot}25 \times 10^9 + 3{\cdot}75 \times 10^5 \\ &\simeq \frac{L_2+L_3}{L_1L_3C} \end{aligned}$$

$$c = \frac{R_2}{L_1L_3C} = 1{\cdot}25 \times 10^{13}$$

The conditions for equations (12) are satisfied, so that

$$\left.\begin{aligned} \beta &\simeq \frac{R_2}{L_2+L_3} \\ \alpha &\simeq \frac{1}{2CR_a} \\ \omega &\simeq \sqrt{\left[\frac{L_2+L_3}{L_1L_3C} - \frac{1}{4C^2R_a^2}\right]} \end{aligned}\right\} \quad . \quad . \quad . \quad (13)$$

and since $\alpha >> \beta$

$$(\alpha-\beta)^2 + \omega^2 \simeq \frac{L_2+L_3}{L_1L_3C}$$

and therefore the numerical coefficient of (6) becomes

$$\frac{Mg}{L_2+L_3}$$

However, since $M = \sqrt{(L_1L_2)}$ and $s = \sqrt{(L_1/L_2)}$, the coefficient can be written as

$$\frac{sg}{1+(L_3/L_2)} \quad . \quad . \quad . \quad . \quad . \quad (14)$$

The values given by (13) and (14) may be substituted in (6).

Before discussing the results just obtained it will be convenient to derive the corresponding quantities for a frame time-base.

3(c) FRAME TIME-BASE

We may take the following magnitudes as being fairly representative of those occurring in the design of a frame scanning system:—

$L_1 = 1\,000$ H; $L_2 = 2{\cdot}5$ H; $L_3 = 10$ mH; $C = 100\ \mu\mu$F; $R_a = 10^4\ \Omega$; $R_1 = 2 \times 10^3\ \Omega$; $R_2 = 10\ \Omega$.

Inserting these values, we find

$$a \simeq \frac{1}{CR_a} = 10^6$$

$$b \simeq \frac{R_a(L_2 + L_3) + R_2L_1}{L_1L_3CR_a} = 3{\cdot}51 \times 10^9$$

$$c = \frac{R_2}{L_1L_3C} = 10^{10}$$

Hence

$$\left.\begin{aligned} \beta &\simeq \frac{R_2R_a}{R_a(L_2 + L_3) + R_2L_1} \\ \alpha &\simeq \frac{1}{2CR_a} \\ \omega &\simeq j\sqrt{\left[\frac{1}{4C^2R_a^2} - \frac{R_a(L_2 + L_3) + R_2L_1}{L_1L_3CR_a}\right]} \end{aligned}\right\} \qquad (15)$$

while the numerical coefficient is approximately equal to

$$\frac{MgR_a}{R_a(L_2 + L_3) + R_2L_1} \quad . \quad . \quad . \quad . \quad (16)$$

Since in this instance ω is imaginary, equation (7) is the appropriate one for indicial transfer admittance. However, the numerical values are such that $(\alpha - \beta)/\omega' \simeq 1$, so that the expression may be simplified to give

$$A(t) = \frac{k}{(\alpha - \beta)^2 - \omega'^2}\left[e^{-\beta t} - e^{-(\alpha - \omega')t}\right] \quad . \quad (17)$$

with sufficient accuracy for most purposes.

Again $L_2 >> L_3$ so that $(L_2 + L_3) \simeq L_2$, which gives

$$\left.\begin{aligned} \beta &\simeq \frac{R_2}{L_2\{1 + (s^2R_2/R_a)\}} \\ \omega' &\simeq \frac{1}{2CR_a} - \frac{R_2}{L_3}\left(1 + \frac{R_a}{s^2R_2}\right) \end{aligned}\right\} \quad . \quad . \quad (18)$$

and for the numerical coefficient

$$\frac{sg}{1 + (s^2R_2/R_a)} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (19)$$

Substituting (18) and (19) in (17) results in

$$A(t) \simeq \frac{sg}{1 + (s^2R_2/R_a)}\left[e^{-\frac{R_2t}{L_2\{1 + (s^2R_2/Ra)\}}} - e^{-\frac{R_2}{L_3}\left(1 + \frac{R_a}{s^2R_2}\right)t}\right] \quad . \quad . \quad . \quad . \quad (20)$$

(4) DISCUSSION OF RESULTS.

The definition given at the beginning of Section (3) states that when the signal applied to the amplifier valve is a unit function the output current and the indicial transfer admittance are numerically equal; hence if the indicial transfer admittance is a function of time the output current is not of the same form as the input signal. This is a particular instance of the general law that undistorted reproduction is obtained only when the indicial transfer admittance is a pure numeric. However, as shown by the analysis, and as is otherwise obvious on purely physical grounds, this condition is unrealizable. Accordingly we have now to decide how much distortion can be tolerated, and what must be the relationship between the values of the circuit components in order that this degree of distortion shall not be exceeded.

Turning back to equations (6), (7), and (8), to make a choice of one of the three possible forms that the indicial transfer admittance can take, it will be found desirable to select that given by (8), for the oscillatory form given by (6) is clearly undesirable, while the function given by (7) takes a longer time to reach its maximum value than does that given by (8).

Hence we require ω to vanish, and in the case of the line time-base (13) shows that this can happen if

$$R_a = \tfrac{1}{2}\sqrt{\left[\frac{L_1L_3}{C(L_2 + L_3)}\right]}$$

or, assuming $L_2 >> L_3$, a desirable state of affairs clearly indicated by (14),

$$R_a = \frac{s}{2}\sqrt{\frac{L_3}{C}} \quad . \quad . \quad . \quad . \quad . \quad . \quad (21)$$

Substituting this in (13) and (14) and replacing $(L_2 + L_3)$ by L_2, (8) now reads as

$$A(t) = sg\left[e^{-\frac{R_2}{L_2}t} - \left\{1 + \frac{t}{s\sqrt{(L_3C)}}\right\}e^{\frac{-t}{s\sqrt{(L_3C)}}}\right] \qquad (22)$$

The goal of a constant value for $A(t)$ is seen to be most closely approached by

(i) making $s\sqrt{(L_3C)}$ as small as possible, in order that the second term within the square brackets in (22) may tend to zero in the shortest possible time, and

(ii) keeping the ratio R_2/L_2 to as low a value as possible, in order that the first exponential term may depart from unity by as little as possible during the time in which we are interested, i.e. during the sweep time.

Considering (i), we can make each of the terms s, L_3, and C, small, either separately or together. Now the magnitude of s is more or less fixed by the amount by which the anode current of the valve can be modulated and by the turns on the deflector coils. For a given maximum permissible swing of anode current and for a given type of deflector coil assembly, the product of s by N, the total number of turns on the deflector coils, is constant. Furthermore, L_3 varies as N^2, so that, under the conditions stated, the term $s\sqrt{L_3}$ is constant. Now, for a given value of the product of magnetic field strength per ampere by deflecting zone length, the inductance is reduced by using ironclad deflector coils; at the same time the resistance of the coils, if wound to occupy a given space, will be reduced if iron is used, since fewer turns will be needed. This, then, is clearly a desirable step.

The larger part of C will be made up of the distributed capacitance of the primary winding of the transformer, so that it is desirable to decrease the number of turns in this winding as far as possible. However, a corresponding reduction in L_2 will be needed if s is to be constant, and condition (ii) shows that it is not possible to proceed very far in this direction.

As is usually the case, the various requirements are in conflict with one another, so that the final design must be, to a large extent, a compromise. It may be observed, however, that a very considerable easing of the difficulty occurs if it is possible to use a valve whose anode-current swing is large; for example, if two valves are available in place of one, then, keeping the secondary winding and the deflector coils unchanged, only one-half of the turns otherwise required have to be wound on the primary. There is then a gain of 2 due to the reduction in s, and a further gain, of somewhat smaller magnitude, in the consequent reduction of the primary capacitance.

When one comes to the frame deflecting system somewhat different considerations are involved, for the very considerable difficulties associated with getting a sufficiently rapid flyback in the line time-base are much selected limits. The rest of the design then proceeds in a quite straightforward manner.

It was pointed out previously in connection with the line time-base that ω could be made to vanish, and (21) implies that this should be done by manipulation of the value of R_a; however, there is no reason why one should not alter either s, L_3, or C, to get the desired result. On the other hand, it is most convenient to alter R_a, increasing it by the insertion of resistance in series with the valve (preferably in the cathode circuit) and decreasing it by connecting resistances in parallel (most conveniently done on the secondary of the transformer).

Fig. 2 shows the indicial transfer admittance of three circuits each having the values given in Section 3(b), except for the value of R_a. The three values of R_a chosen correspond to the conditions represented by

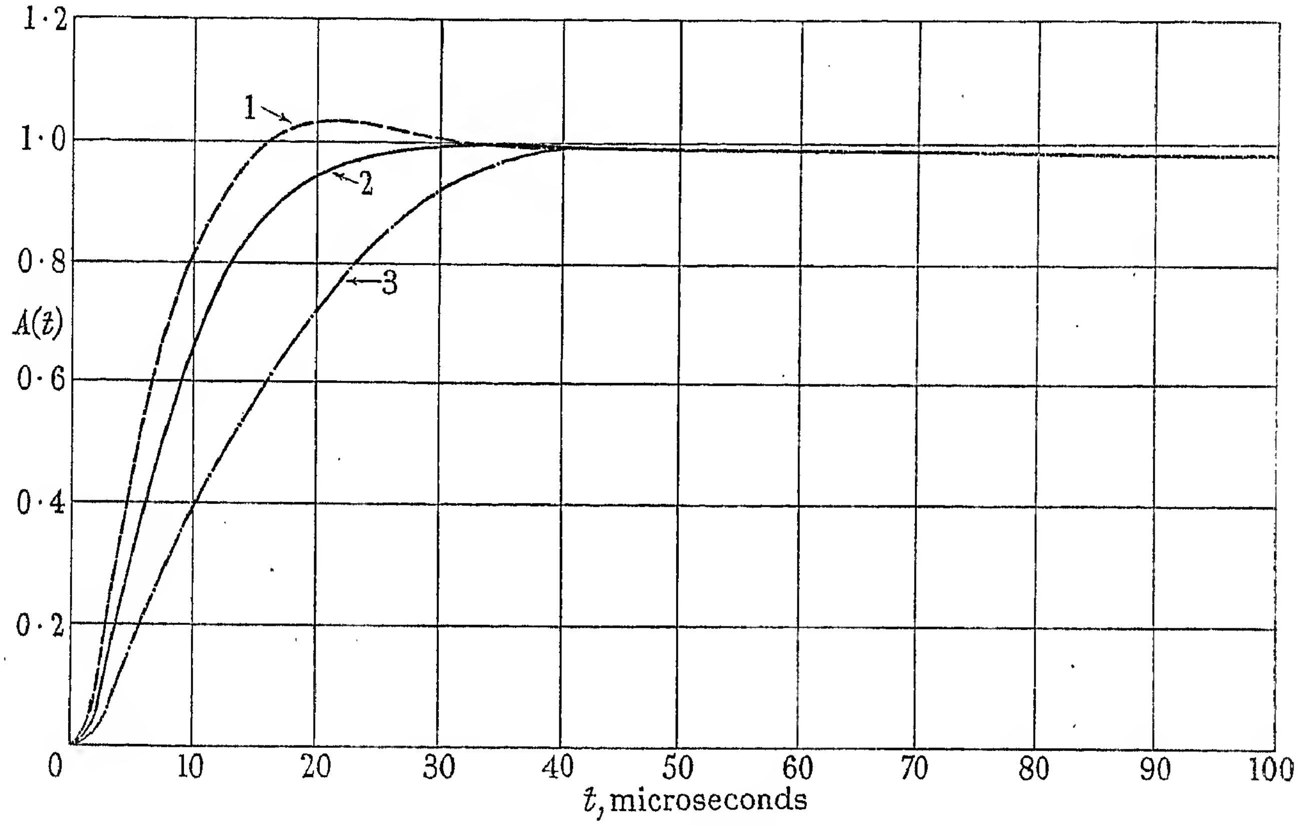

Fig. 2.—Indicial transfer admittance, with numerical factor taken as unity.

(1) $R_a = 6 \times 10^4$ ohms.
(2) $R_a = 4{\cdot}46 \times 10^4$ ohms.
(3) $R_a = 3 \times 10^4$ ohms.

reduced. Actually, most of the difficulties are connected with obtaining the undistorted transfer from primary to secondary of slowly changing currents and potentials. Attention is directed, therefore, to the first exponential term in (20).

Assuming for the moment that R_2 and R_a are constant, it will be noted that the numerical value of (20) exhibits a maximum with respect to s, its value being $\frac{1}{2}sg$, and occurs when $s = \sqrt{(R_a/R_2)}$. If this value is adopted, (20) becomes

$$A(t) = \tfrac{1}{2}\sqrt{\frac{R_a}{R_2}} \cdot g\left[e^{-\frac{R_2}{2L_2}t} - e^{-\frac{2R_2}{L_3}t}\right] \quad . \quad . \quad (23)$$

If L_3 is known R_2 is at once fixed by the time required for the second exponential term to become vanishingly small, and the value of L_2 is then so chosen that the distortion of the sweep caused by the deviation from unity of the first exponential term falls within the equations (6), (7), and (8). It will be seen that in the most favourable case [curve 2, corresponding to equation (8)], it takes approximately 33 microseconds for $A(t)$ to rise to its maximum value; at the end of 100 microseconds $A(t)$ has fallen to 98 % of its maximum value. Anticipating the results of the next Section, when the signal to be amplified is of saw-tooth wave-form the flyback time is approximately equal to the time taken by $A(t)$ to rise to its maximum value, while the linearity of the sweep depends mainly on the first exponential term ($e^{-\beta t}$) differing by only a small amount from unity. Hence while the values of the circuit constants are quite satisfactory from the point of view of linearity, the flyback time is excessive. These points will be illustrated more clearly in the next Section.

Throughout the analysis it has been assumed that $M^2 = L_1L_2$, following condition (d) of Section (2). When this condition is not satisfied but the leakage is small, the

main effect is to increase the effective value of L_3 by the leakage inductance of the transformer, referred to the secondary. A subsidiary effect, which can occur under certain circumstances, is for damped oscillations to be set up during the flyback stroke, such oscillations having a frequency which is almost entirely dependent upon the leakage inductance and the inter-winding capacitance of the transformer. It is for this reason that it is advisable to insert an earthed screen between the windings.

(5) REPRODUCTION OF SAW-TOOTHED WAVE-FORM

Having determined the response of the circuit to the unit function, we are now in a position to formulate the response to the saw-tooth wave-form shown in Fig. 3. The most direct way of doing this is by application of the superposition theorem; in practice, however, this is not particularly convenient and the author prefers to adopt a rather simpler method.* The basis of this method is that the saw-toothed grid wave-form of amplitude V and period T is written as

$$V\frac{t}{T} - V\Sigma_n 1_{nT} \quad . \quad . \quad . \quad . \quad . \quad (24)$$

The Σ notation implies the summation of a series of

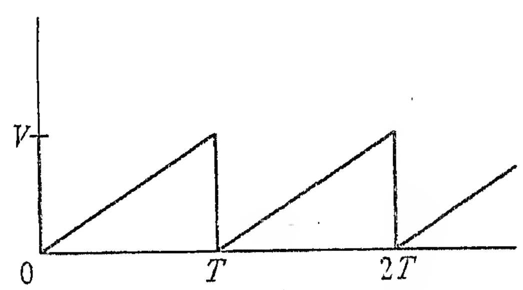

Fig. 3.—Saw-tooth wave-form of grid potential.

unit functions applied at times $t = T, 2T, \ldots nT$, n being a positive integer.

We require, then, the solution of the equation

$$\frac{1}{p}(p+\beta)(p+\alpha+j\omega)(p+\alpha-j\omega)i_2 = kV\left\{\frac{t}{T} - \Sigma_n 1_{nT}\right\} \quad . \quad . \quad . \quad (25)$$

So far as the first term on the right-hand side is concerned, we require only the particular integral, since the process is regarded as having been going on for a long time prior to the time $t = 0$. Actually, we seek a solution valid only for

$$0 \leqslant t \leqslant T$$

The particular integral is seen, by inspection, to be of the form $i'_2 = C$. Substituting, we have

$$\beta(\alpha + j\omega)(\alpha - j\omega)C = \frac{kV}{T}$$

so for the particular integral we have

$$i'_2 = \frac{kV}{\beta T} \cdot \frac{1}{\alpha^2 + \omega^2} \quad . \quad . \quad . \quad . \quad . \quad (26)$$

* This conception is due to Mr. L. H. Bedford, who very kindly assisted with the analysis of this Section, and to whom the author wishes to express his appreciation and thanks.

For the second term on the right-hand side we can write the solution immediately as

$$i''_2 = -kV\sum\frac{1}{(\alpha-\beta)^2+\omega^2}\left[e^{-\beta t} - e^{-\alpha t}\left(\cos\omega t + \frac{\alpha-\beta}{\omega}\sin\omega t\right)\right] \quad . \quad (27)$$

where the Σ notation now implies that we have to take the sum of an infinite series of terms in which $(t + nT)$ is written for t, n having all integral values between 0 and ∞.

The series corresponding to the first term in the bracket in (27) is

$$e^{-\beta t}(1 + e^{-\beta T} + e^{-2\beta T} + \ldots) = e^{-\beta t}/(1 - e^{-\beta T}) \quad . \quad (28)$$

For the second term we need take only the first member of the series, since $1/\alpha$ is short compared with T. Hence we reach the solution

$$i_2 = \frac{kV}{\beta T(\alpha^2+\omega^2)} - \frac{kV}{(\alpha-\beta)^2+\omega^2}\left[\frac{e^{-\beta t}}{1-e^{-\beta T}} - e^{-\alpha t}\left(\cos\omega t + \frac{\alpha-\beta}{\omega}\sin\omega t\right)\right] \quad . \quad (29)$$

Bearing in mind that $\beta T << 1$

and $\beta << \alpha$

we approximate as follows:—

$$i_2 \simeq \frac{kV}{\beta T(\alpha^2+\omega^2)} - \frac{kV}{\alpha^2+\omega^2-2\alpha\beta}\left[\frac{1-\beta t}{\beta T - \frac{1}{2}\beta^2T^2} - e^{-\alpha t}\left(\cos\omega t + \frac{\alpha}{\omega}\sin\omega t\right)\right]$$

$$\simeq \frac{kV}{\beta T(\alpha^2+\omega^2)} - \frac{kV}{\alpha^2+\omega^2}\left(1 + \frac{2\alpha\beta}{\alpha^2+\omega^2}\right)\left[\frac{1}{\beta T}\frac{1-\beta t}{1-\frac{1}{2}\beta T} - e^{-\alpha t}\left(\cos\omega t + \frac{\alpha}{\omega}\sin\omega t\right)\right]$$

$$\simeq \frac{kV}{\alpha^2+\omega^2}\left[\frac{1}{\beta T}\left\{1 - \left(1+\frac{2\alpha\beta}{\alpha^2+\omega^2}\right)(1-\beta t)(1+\tfrac{1}{2}\beta T)\right\} + \left(1+\frac{2\alpha\beta}{\alpha^2+\omega^2}\right)e^{-\alpha t}\left(\cos\omega t + \frac{\alpha}{\omega}\sin\omega t\right)\right]$$

$$\simeq \frac{kV}{\alpha^2+\omega^2}\left[\frac{1}{\beta T}\left(\beta t - \tfrac{1}{2}\beta T - \frac{2\alpha\beta}{\alpha^2+\omega^2}\right) + e^{-\alpha t}\left(\cos\omega t + \frac{\alpha}{\omega}\sin\omega t\right)\right]$$

$$= \frac{kV}{\alpha^2+\omega^2}\left[\frac{t}{T} - \frac{1}{2} - \frac{2\alpha}{(\alpha^2+\omega^2)T} + e^{-\alpha t}\left(\cos\omega t + \frac{\alpha}{\omega}\sin\omega t\right)\right] \quad . \quad (30)$$

The above is the general solution of the problem. However, in the frame-scanning system ω will be imaginary and the solution is then

$$i_2 = \frac{kV}{\alpha^2-\omega'^2}\left[\frac{t}{T} - \frac{1}{2} - \frac{2\alpha}{(\alpha^2-\omega'^2)T} + e^{-\alpha t}\left(\cosh\omega' t + \frac{\alpha}{\omega'}\sinh\omega' t\right)\right] \quad . \quad (31)$$

while if ω vanishes, as we have seen it may do in the case of the line time-base, the solution becomes

$$i_2 = \frac{kV}{\alpha^2}\left[\frac{t}{T} - \frac{1}{2} - \frac{2}{\alpha T} + (1 + \alpha t)e^{-\alpha t}\right] \quad . \quad (32)$$

The curves of Fig. 4 show the result of applying the saw-tooth wave to the line amplifier discussed in Section 3(*b*). The values of R_a, however, are those which were used in calculating the curves of Fig. 2, and the curves marked 1, 2, 3, correspond to those similarly numbered in that Figure. The value of the constant $kV/(\alpha^2 + \omega^2)$ is taken as unity and that of T as 10^{-4} sec.

Some features of considerable interest and importance may be pointed out. Firstly, the peak-to-peak amplitude of the current wave decreases with decrease in the value of R_a. Secondly, the maximum amplitude of the positive swing is greater than that of the negative swing, a result seen in practice as an apparent shift of the centre of the raster. Thirdly, when R_a is changed the corresponding change in the negative peak amplitude is much greater than is that of the positive peak.

So far as the present author is aware, these effects have not been mentioned previously in the literature of the subject, although they are recognized in practice; certainly none of them appears to be suggested by the exponents of the Fourier method of attack, who have produced syntheses of saw-tooth wave-forms which are chiefly remarkable for the fact that they indicate distortion of the same character occurring at the beginning and end of the sweep!

It will be noticed that the flyback time corresponds to the time taken for the indicial transfer admittance to rise to its maximum value and that, as previously suggested, the preferable form of the result is that given by equations (8) and (32) and by curve 2. The flyback time is excessive; this in no way invalidates the method or the results, but simply indicates that the values chosen would be unsatisfactory in a time-base intended for use with signals conforming to the existing standards, and that a re-design is needed.

A feature of considerable interest from the practical point of view, which is apparent on comparing Figs. 2 and 4 and which has been suggested before but may be emphasized here, is that the larger part of the information required for design purposes is contained in equations (6), (7), and (8), taken in conjunction with the explanations given in Sections 3(*b*), 3(*c*), and (4).

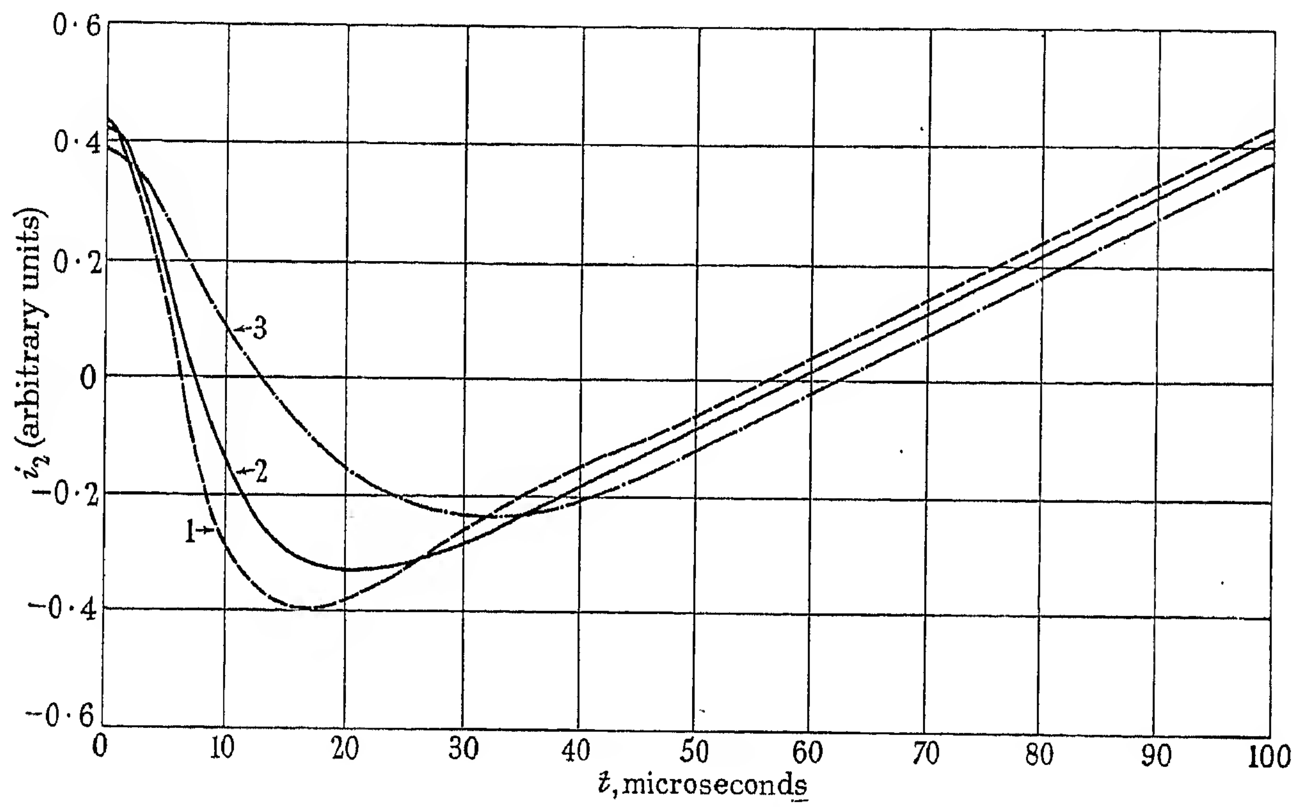

Fig. 4.—Current through deflector coils, in arbitrary units (numerical factor taken as unity).

(1) $R_a = 6 \times 10^4$ ohms.
(2) $R_a = 4{\cdot}46 \times 10^4$ ohms.
(3) $R_a = 3 \times 10^4$ ohms.

(6) ANODE POTENTIAL EXCURSION

The swing of anode voltage occurring during the flyback period can rise to very high values, and since this is a matter of some importance the author will now proceed to calculate this quantity.

The anode voltage, neglecting the steady supply potential, will be denoted by E_a, and reference to Fig. 1(*b*) and equation (2) shows that

$$E_a = -\left\{(L_1 p + R_1)i_1 - Mpi_2\right\} \quad . \quad . \quad (33)$$

From (3)

$$E_a = -\left[\frac{R_1(L_2 + L_3) + R_2 L_1}{M} + \frac{L_1 L_3}{M}p + \frac{R_1 R_2}{Mp}\right]i_2$$

or, neglecting L_3 in comparison with L_2 in the first term,

$$E_a = -\left[\frac{R_1}{s} + sR_2 + sL_3 p + \frac{R_1 R_2}{Mp}\right]i_2 \quad . \quad (34)$$

Substituting the value of i_2 given by (30),

$$E_a = \frac{-kV}{\alpha^2+\omega^2}\left[\left(\frac{R_1}{s}+sR_2\right)\left\{\frac{t}{T}-\frac{1}{2}-\frac{2\alpha}{(\alpha^2+\omega^2)T}+e^{-\alpha t}\left(\cos\omega t+\frac{\alpha}{\omega}\sin\omega t\right)\right\}+sL_3\left(\frac{1}{T}-\frac{\alpha^2+\omega^2}{\omega}e^{-\alpha t}\sin\omega t\right)\right]-\frac{R_1R_2}{M}\int_0^t i_2 dt \quad (35)$$

In the important case when $\omega = 0$, (35) simplifies considerably and becomes

$$E_a = \frac{-kV}{\alpha^2}\left[\left(\frac{R_1}{s}+sR_2\right)\left\{\frac{t}{T}-\frac{1}{2}-\frac{2}{\alpha T}+(1+\alpha t)e^{-\alpha t}\right\}+sL_3\left(\frac{1}{T}-\alpha^2 te^{-\alpha t}\right)\right] \quad . \quad . \quad (36)$$

Fig. 5 illustrates these results. As before, the curves 1, 2, 3, apply to the line time-base of Section 3(*b*), but

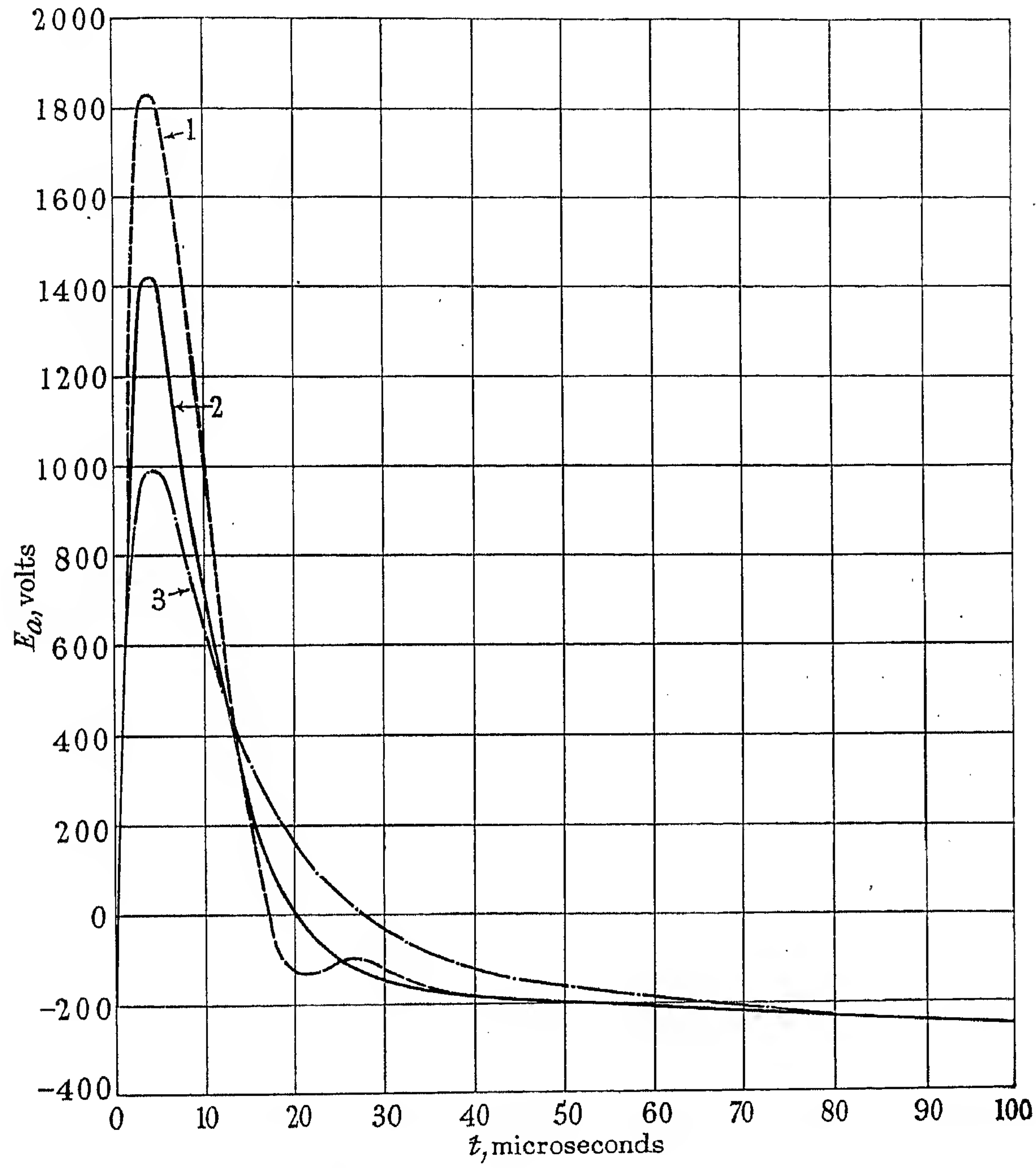

Fig. 5.—Anode-potential variations.

(1) $R_a = 6 \times 10^4$ ohms.
(2) $R_a = 4 \cdot 46 \times 10^4$ ohms.
(3) $R_a = 3 \times 10^4$ ohms.

The value of the integral is easily found to be

$$\frac{-kVR_1R_2}{m(\alpha^2+\omega^2)}\left[\frac{t^2}{2T}-\frac{1}{2}t+\frac{2\alpha}{\alpha^2+\omega^2}\left(1-\frac{t}{T}\right)+\frac{e^{-\alpha t}}{\alpha^2+\omega^2}\left(\frac{\omega^2-\alpha^2}{\omega}\sin\omega t-2\alpha\cos\omega t\right)\right]$$

but since its magnitude is so small compared with that of the other terms of (35) it may be neglected.

since we wish to find the actual numerical value of E_a we have adopted the following additional data:—

$$g = 4 \times 10^{-3}\ \text{amp./volt}, \quad V = 12 \cdot 5\ \text{volts}.$$

During the earlier stages of the flyback only the last group of terms in the square brackets in (35) and (36) is important, and since the magnitude of the contribution to the total voltage from this group of terms is directly proportional to sL_3, the importance of making this

product small is again emphasized. Furthermore, this group of terms in (36) has a maximum value of

$$sL_3\left(\frac{1}{T} - \frac{\alpha}{e}\right) \quad . \quad . \quad . \quad . \quad . \quad (37)$$

occurring when $\alpha t = 1$, and since it is desirable that $\alpha >> 1/T$ the maximum positive swing of E_a is approximately equal to

$$E_{a_{max}} \simeq \frac{kVsL_3}{\alpha e}$$

$$= \frac{2}{e}R_a g V \quad . \quad . \quad . \quad . \quad . \quad (38)$$

or

$$E_{a_{max}} = 0\cdot 368\sqrt{\frac{L_3}{C}} \cdot gsV \quad . \quad . \quad . \quad . \quad (39)$$

The minimum value of E_a occurs when $t = T$, and from (36) this is

$$E_{a_{min}} = -\frac{kV}{\alpha_2}\left\{\left(\frac{R_1}{s} + sR_2\right)\left(\frac{1}{2} - \frac{2}{\alpha T}\right) + \frac{sL_3}{T}\right\}$$

$$\simeq -\frac{kVs}{\alpha_2}\left\{\frac{1}{2}\left(\frac{R_1}{s^2} + R_2\right) + \frac{L_3}{T}\right\}$$

$$= -gV\left\{\frac{s^2L_3}{T} + \frac{1}{2}(R_1 + s^2R_2)\right\} \quad . \quad . \quad . \quad . \quad (40)$$

These results are of considerable practical importance. Equation (40) gives the amount by which the anode potential falls below the supply potential, and as the minimum anode voltage at which the output valve can operate linearly is known, the required H.T. supply voltage becomes known. On the other hand, equations (38) and (39) give the peak anode voltage, and therefore supply information about the voltage ratings of the components and the suitability of various physical layouts.

(7) CONCLUSION

The foregoing analysis exhibits fairly completely the behaviour of time-base amplifiers used for magnetic deflection, and gives sufficient information for their design to be undertaken. The condition of zero magnetic leakage employed throughout the discussion was imposed for two reasons. Firstly, it simplified the algebra, which was sufficiently complicated in any case. Secondly, and more importantly, the results obtained are immediately applicable to those circuits in which the deflector coils are fed directly from the amplifier valve, the change in notation required being obvious.

(8) ACKNOWLEDGMENTS

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BIBLIOGRAPHY

(1) M. von Ardenne: "Der Fernsehempfang," *Fernseh und Tonfilm*, 1937, vol. 2, p. 13.

(2) F. J. Somers: "Scanning in Television Receivers," *Electronics*, October, 1937, p. 18.

(3) M. von Ardenne: "Distortion of Saw-tooth Waveforms," *ibid.*, November, 1937, p. 36.

(4) D. M. Johnstone: "Design of Line-Scanning Transformers," *Journal of the Television Society*, 1936, vol. 2, p. 138.

(5) J. R. Carson: "Electric Circuit Theory and the Operational Calculus" (First edition, p. 24).

(6) V. Bush: "Operational Circuit Analysis," p. 380. (A very complete list of operational formulae is given in this work.)

THE LOCALIZATION OF EXPOSED BREAKS IN SUBMARINE CABLES*

By A. L. STOREY, Associate Member.†

(*Paper first received* 22*nd November*, 1938, *and in revised form* 9*th May*, 1939.)

SUMMARY

This paper gives a brief description of the methods used in localizing breaks in submarine cables, and an account of measurements made with the purpose of verifying the laws relating to breaks. From these, and similar measurements, certain conclusions are drawn which, when applied to break tests, should reduce errors in localization.

As a result of a study by the author of the laws governing break tests, a new method is presented of computing the resistance to a break from measurements made in a known manner.

INTRODUCTION

Over a period of 60 or 70 years a number of tests have been introduced for the purpose of localizing breaks in submarine cables. Descriptions of the earlier ones are to be found collected in textbooks, and of the later ones in scattered papers contributed to the technical Press. Despite the fact that there are a number of tests, some more generally reliable than others, there is none upon which one can always rely. It is sometimes necessary, and always advisable, to use more than one method in localizing a break.

It is the purpose of the present paper to describe the various tests briefly, and to give an account of measurements made by the author with the ultimate object of increasing the accuracy of break localizations.

The examples that are given are almost entirely of tests and measurements made through artificial lines such as are used for balancing submarine cables. The resistances of the lines varied from a few ohms to 4 000 ohms, and the capacitance from 1 to 300 μF. The testing apparatus was that normally used at a cable station. The actual exposures were made in the following way. A short length of cable core was joined in series with the artificial line, and a short length of the conductor was bared and inserted in salt water. Sometimes sea-water was used, but generally salt water of density $1 \cdot 035$ g. per cm^3. A cylinder of galvanized iron or zinc in the salt water represented the sheathing of the cable, and was connected to the earth return. It follows, therefore, that the observations relating to these measurements do not apply to breaks exposed in fresh water.

In the examples the resistance of the conductor up to the break has been deducted from the observed values, so that the figures given for the balances represent the resistances of the end, whilst the results represent the actual errors in the localization.

When a break occurs in a submarine cable the end of the copper conductor may be exposed in salt water, or it may be sealed by guttapercha pulled out over the end, or it may be in an intermediate condition. In the first case the position of the break would be determined by resistance measurements, and in the second case by capacitance measurements. In the third case, one or other of these methods would be employed, the choice being dependent upon the ability to open out the leak or to seal it by electrical means. The present paper is concerned with the first class of breaks. Such exposures may, for convenience of description, be arbitrarily divided into groups according to their areas, in the following manner:—

(*a*) Large, in which the area exceeds $0 \cdot 5$ sq. in.
(*b*) Medium, in which the area is between $0 \cdot 2$ and $0 \cdot 5$ sq. in.
(*c*) Small, in which the area is between $0 \cdot 05$ and $0 \cdot 2$ sq. in.
(*d*) Very small, in which the area is less than $0 \cdot 05$ sq. in.

The majority of breaks belong to group (*b*).

METHODS OF WHEATSTONE BRIDGE BALANCING

The apparatus available at a cable station for resistance measurements includes an accurate Wheatstone bridge, a Sullivan or other moving-coil galvanometer, a universal shunt, a three-range milliammeter, variable resistors, and the necessary keys and batteries.

Measurements on the conductors of submarine cables may be made by Wheatstone-bridge balances taken to true (or scale) zero, to false zero, or to reduced-current zero. Allowance has to be made for the large capacitance of the cable and for the frequent presence of electromotive forces in the cable and earth-return circuit.

To obtain a balance to true zero the battery is applied, and after sufficient time for the cable to receive its surface charge and absorbed charge the balancing arm is adjusted until there is no current through the galvanometer. In the presence of an earth current, the result of the measurement gives the value of $x \pm e/i$, where x is the resistance of the conductor, e is the e.m.f. acting in the unknown arm, and i is the current in that arm. e/i is called the "ohmic equivalent" of the earth current. The positive sign is applicable when the earth current opposes the testing current. A correction is therefore necessary in order to get the true value of x. When the earth current is steady, Mance's method may be used to eliminate its effect. (Mance's test is well known; it is described later on page 418.)

The effects of earth currents are usually eliminated by balancing to false zero or to reduced-current zero. In a

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balance to false zero, the balancing arm is adjusted until the current through the galvanometer is the same whether the testing battery is applied or not. In a balance to reduced-current zero, the balancing arm is adjusted until the current through the galvanometer is the same with the full testing current flowing to line as it is with a reduced current flowing. Usually the reduced-current zero is observed with a current equal to half the full testing current.

The manner in which a false-zero balance is taken varies according to the behaviour of the earth current in the line and the capacitance of the line. When a steady earth current is flowing in a line the end of which is well earthed, the testing battery is applied and, after the transient currents due to surface charge and absorbed charge have disappeared, the deflection on the galvanometer when the steady current is flowing in the line is observed. Then the battery key is released, and the false zero, that is to say the deflection due to the earth current alone, is read after the complete discharge of the line. The balancing arm is adjusted until these two deflections are equal. It is necessary to observe the false zero after every alteration made in the bridge, so that balance is finally reached after a succession of alternate observations of galvanometer deflection with and without the battery applied.

When the e.m.f. in a line is variable, or when there is a polarization e.m.f., as in a faulty line, one cannot wait until the complete discharge (i.e. including the absorbed charge) of the line has taken place to read the false zero, because the e.m.f. may alter before the zero is read. It is therefore observed as soon as the surface charge has issued from the cable. An endeavour is made by watching the movement of the " spot " during and after this discharge to detect the change in speed which occurs when the surface charge has ceased to flow out. The position of this change in speed is taken as the false zero. When the discharge from the line is considerable, the galvanometer must be short-circuited during the initial part of the discharge and re-introduced in time to show the later part of the discharge.

In the presence of a variable earth current the following procedure is helpful. As the " spot " moves across the scale owing to the capacitance (and absorption) charge or discharge, if it crosses the previous observed deflection before the time it should be read it indicates more resistance required in the bridge, and vice versa. By making a mental note of the " mores " and " lesses," the preponderance of one or the other enables the effect of the variable earth current to be averaged.

When the pause or the change in speed is not sufficiently distinct, the observer must estimate the time that is occupied by the discharge of the surface charge. The position of the spot at that number of seconds after releasing the battery key is taken as the false zero. While making a preliminary estimate of the length of this false-zero interval, the galvanometer may with advantage be heavily shunted.

The false-zero balance may also be taken to " swings." The false-zero interval having been estimated, the battery is applied, and after conditions have become steady the galvanometer key is depressed for a short time, and the resulting swing of the " spot " is taken as proportional to the potential difference between the ends of the cross-circuit. Then, when the " spot " has fallen back and come to rest on scale zero, the battery key is released and after the false-zero interval the galvanometer key is depressed for the same period of time as before. The resulting swing is taken as proportional to the potential difference between the ends of the cross-circuit, and as indicating the false zero. Careful and regular manipulation of the keys is necessary during a balance to swings. Apart from the necessity of correctly estimating the false-zero interval, the period of depression of the galvanometer key must not be too great. With too long a depression the deflection with the battery applied reaches the peak of its swing and then continues to grow slowly, whilst without the battery applied, under similar circumstances, the deflection reaches the peak of its swing and then diminishes. Some skill is thus required in taking a balance of this kind.

In the case of tests taken on a broken cable, there is usually a polarization e.m.f. at the exposure. Its value begins to drop as soon as the testing current is withdrawn. In consequence the false zero, which cannot be read until the cable is discharged, is due to something less than the full polarization e.m.f., and too high a value is assigned to the resistance of the unknown arm. The formula applicable to a bridge balanced to false zero, and the effect of a delayed reading of the false zero, are examined in Appendix 1. It will be seen there that the ordinary bridge formula applies to a false-zero balance taken with a steady e.m.f. in the line, but that when the e.m.f. falls before the false zero can be read the result is high by the amount de/di ohms, where de is the change in the e.m.f. in the line and di is the change in the current in the line.

On a short line the discharge through the galvanometer is small and may be reduced further by joining a resistance in series with the line during the test. In that case the galvanometer may be left continuously in circuit. On a very short line the capacitance of which is so small that it produces no " kick," balance is taken to " immediate " false zero. Such a balance is obtained when, on removing the battery, the " spot " remains stationary for a moment before moving towards scale zero or towards its final zero.

The difficulty of fixing the zero when testing a faulty cable is almost entirely removed when balances are taken to reduced-current zero. The reduced current helps to maintain the polarization e.m.f. at the fault. When the current is reduced there is a quick initial drop in this e.m.f., followed by a slow small drop to a final steady value. The balance may be taken to the final steady reduced-current zero, or it may, as is usually done in break tests, be taken to a reduced-current zero read after the same interval as in a false-zero balance. The drop of polarization during the interval between the reduction of the current and the reading of the zero is small, and the balance obtained only includes a small depolarization error.

The reduced current is usually one-half of the full testing current. With this reduction the sensitiveness of the bridge balance is only half of what it would be in a false-zero balance taken with the same testing current, but this loss in sensitiveness is more than compensated by the gain in accuracy in fixing the position of the zero. The formula applicable to such a balance is derived in

Appendix 1, where it will be observed that the false-zero balance may be regarded as a particular case of the reduced-current zero balance.

RESISTANCES AND ELECTROMOTIVE FORCES PRESENT IN A BROKEN CABLE

In a broken submarine cable the following resistances and electromotive forces are present:—

(*a*) The resistance of the conductor up to the break. Its value is constant, and is the unknown the value of which is required.

(*b*) The contact resistance between the copper and sea-water. This is a function of the current density. For a given exposure, increasing the current reduces the contact resistance.

(*c*) The resistance of the electrolyte (sea-water) and of the return circuit. The resistance of the electrolyte is comparatively small, and is almost entirely localized in the immediate neighbourhood of the exposure, for there alone is the cross-sectional area of the path of the current small. When, however, the exposure is very small and is of such a form and position that it is not in direct contact with the mass of the sea, then the resistance of the electrolyte may reach a score or more ohms. The resistance of the return path from the neighbourhood of the break to the testing station's earth is negligible.

The contact resistance and the electrolytic resistance are usually lumped together, and their sum is called the "end resistance."

(*d*) The primary fault e.m.f. produced by the iron (sheathing), copper, and sea-water. This is usually about $\frac{1}{3}$ volt, and as the copper is the positive pole of the couple it assists the negative testing current.

(*e*) The polarization e.m.f. caused by the passage of the testing current through the water. This opposes the testing current and overcomes the primary fault e.m.f. The p.d. between the exposed copper and earth, measured immediately after testing with a negative current of 20 mA, has, on a medium-sized exposure, a value of about 0·3 volt, the copper being negative with respect to earth. The value is slightly smaller after testing with smaller currents.

(*f*) The e.m.f. corresponding to differences in earth potential between the testing station and the break. The effect of this is largely reduced by balancing to false zero, and almost entirely eliminated by balancing to reduced-current zero.

POLARITY AND STRENGTH OF TESTING CURRENTS

Except on breaks that behave abnormally, tests are always made with negative to line. The electrolysis of the salt water which then takes place causes the generation of hydrogen at the surface of the copper. For some seconds after the first application of the current the hydrogen that is produced adheres to the copper: then it is evolved, and after a short time a condition of equilibrium is reached, hydrogen escaping as fast as it is produced. The presence of hydrogen has two effects. It increases the resistance of the end up to a certain limit depending upon the current density, and it sets up a back-e.m.f. of polarization. The end resistance soon reaches this limiting value, and thereafter remains constant so long as the current strength is unaltered. On the other hand, when tests are made with positive to line, cuprous chloride is produced at the surface of the copper. On account of its low solubility it remains there (unless the end is agitated), so that the thickness of the coating is proportional to the current strength and to the time for which it flows. As the chloride is a poor conductor its presence raises the resistance of the end by an amount which increases with time. The end resistance therefore does not follow a simple law, and the amount to be allowed for it is so indefinite that tests taken with positive to line are usually of little value. As an exception, when the free escape of hydrogen is prevented by the condition or position of the end better results are sometimes obtained with positive to line.

The strengths of testing currents should be such that balances are steady, vary in a regular manner when the current is altered, and show adequate sensitiveness. These requirements are usually satisfied on a normal exposure with currents of 3 or 4 to 25 mA. On a larger exposure larger currents may be, but are not often, used. On a small exposure, as will be explained later, currents not exceeding 10 mA are often necessary.

PRELIMINARY OBSERVATIONS ON A BROKEN CABLE

When a cable is reported as broken, and this condition is confirmed by the failure to receive the call of the distant station on a sensitive galvanometer, the cable is connected to the test set. The resistance between the conductor and earth is measured, and it is at once evident whether the broken conductor is insulated, exposed in salt water, or making a dead earth.

Assuming that there is a break exposed in salt water, then balances are taken to false zero with different current strengths and both polarities. The object of these is to obtain information about the nature and the behaviour of the exposure, and to ascertain the testing conditions that are likely to give the steadiest balances. If the behaviour appears to be normal, break tests are taken at once. If not, then negative is applied for some time to try to clean the end. If that should fail, then a few balances with negative and positive alternately would be tried, or slow reversals of current would be applied for a time. Treatment of this kind is often successful after some delay, and break tests can then be taken.

Lumsden's Method

This is one of the oldest break tests. It gives the resistance of the conductor up to the break plus the end resistance when the latter is at a minimum value. An arbitrary deduction is made from the result, its amount being estimated from the behaviour of the break during the test.

As a preliminary, positive is applied to line. The effects of earlier negative testing currents are thus removed, and a thin coating of copper chloride is deposited on the end. This causes the end resistance to rise. Then the negative current is applied and the resistance falls while the chloride is being cleaned off. The fall in resistance is followed on the bridge, balance being taken to false zero. (The false zero changes during the course

of the test, and it must therefore be observed after each application of the negative testing current. The test thus necessitates a succession of observations alternately with and without the battery applied.) The resistance reaches a minimum value, and then, after hydrogen appears, it begins to rise again. The length of time for which the balance remains within an ohm of its minimum value, and the slowness and steadiness with which it eventually rises are useful indications of the size of the exposure. This minimum is the numerical result of the test. It cannot be low since it includes some end resistance. The nearest to the correct position is obtained with the largest testing current normally used. When, on account of unsteadiness with such a current, or on account of the distance to the break, a smaller current is used, a higher result is obtained.

The Lumsden is from 5 to 10 ohms high in the case of large and medium exposures, and up to about 20 ohms with small exposures. For very small exposures such as those that require testing currents below a maximum of 10 mA for satisfactory localizations by other break tests, the Lumsden balance is 20 to 40 ohms high. Those still smaller exposures which behave abnormally with currents of less than 10 mA will usually give Lumsden balances much more than 40 ohms high.

Table 1 illustrates the behaviour of four different exposures in 130/130 core, ranging from average size to very small. The area of the largest was roughly $\frac{1}{8}$ sq. in.

Table 1

Length of exposure	$\frac{3}{4}$ in.	$\frac{1}{4}$ in.	$\frac{1}{8}$ in.	Cut flush with gutta-percha
False zero balance with 20 mA	20 ohms	25 ohms	30 ohms	43 ohms
R.C. zero balance with 20 mA red, to 10 mA	14 ohms	16·5 ohms	20 ohms	30 ohms
Lumsden balance. Lowest with negative after positive	10 ohms	12 ohms	16 ohms	27 ohms
Time during which balance steady at the minimum value	12 sec.	6 sec.	3 sec.	1 sec.

Schaefer's Method

In this method balances are taken to true zero. A bridge measurement taken in this way gives the sum of the resistance of the cable up to the break, the end resistance, and the ohmic equivalent of the various electromotive forces in the unknown arm.

The effect of such electromotive forces as are not due to the action of the testing current is eliminated in the following manner. Before the resistance measurement is made, the value of the e.m.f. acting in the cable and earth return circuit is measured, and its ohmic equivalent is later calculated for each of the testing currents used. The ohmic equivalent is added to the observed resistance values when the earth current acts in the same direction as the testing current, and is subtracted from them when it opposes.

Schaefer's law says that the end resistance observed with such corrected true zero balances varies inversely as the 1·3th root of the current passing through the break, and the end resistance can therefore be written as equal to $m/\sqrt[1\cdot3]{i}$, where i is the current (in mA) and m is a constant whose value depends upon the size of the exposure. The term "end resistance" used in this connection thus includes contact resistance, electrolytic resistance, and the ohmic equivalent of any electromotive forces introduced by the action of the testing current.

Two balances are taken to true zero with currents of ni and i mA respectively. Then if B and A are the corresponding corrected bridge readings,

$$B = x + m/\sqrt[1\cdot3]{ni}$$
$$A = x + m/\sqrt[1\cdot3]{i}$$

whence

$$x = B - (A - B)\frac{1}{\sqrt[1\cdot3]{n} - 1}$$

The resistance, in ohms, to the break can therefore be determined from the results of one pair of measurements. In practice, a number of such pairs are taken, and the mean of all results that are not behaving abnormally is taken as the probable correct result. If the current ratio, n, is made equal to 2·46, then the formula reduces to $x = B - (A - B)$.

A graphical method of solution is widely used. A number of balances are taken with various currents between 20 and 3 mA, and after the balance with the smallest of the series has been obtained a return is made to the balance with the largest current in order to make sure that no change has taken place in the end. The values of $1/\sqrt[1\cdot3]{i}$ are then plotted against the corresponding corrected bridge readings. The best straight line is drawn among the plotted points, and is produced to cut the resistance axis. The resistance up to the break is given by the value at which the line cuts the resistance axis. The method shares with other graphical methods the advantages that it helps to give a picture of the behaviour of the end, and that it tends to smooth out the effects of errors of observations and of small irregularities. Any marked tendency to curvature in the graph shows that there is a considerable departure from Schaefer's law.

The Schaefer method has the advantage that balances are taken to true zero and that they can be taken with considerable precision. It is most useful when there is

no earth current present, the primary fault e.m.f. being then ignored.

The fact that other formulae are used or have been used for balances taken to true zero indicate that departures from the law $\lambda = 1\cdot 3$ (where λ represents the root) are met with. A form of corrected Mance test has the formula $x = B - 1\cdot 5(A - B)$, which implies that $\lambda = 1\cdot 35$, while Rymer Jones's formula $x = B - 1\cdot 57(A - B)$ implies that $\lambda = 1\cdot 4$. (B and A are balances with currents in the ratio of 2 to 1). Schaefer, too, advised that the current ratio should not exceed 3 to 1, "owing to the divergence of the law when currents of high ratio are used."

Table 2

Approximate area of exposure	Value of m	Value of λ
sq. in.		
0·4	275	1·4
0·3	310	1·35
0·2	310	1·35
0·1	330	1·35

A number of measurements made by the author at various times with the purpose of testing the law have given values of λ ranging from 1·2 to 1·55, and occasionally with small exposures still higher values. In one particular group, in which sea water from Brighton was used, the results shown in Table 2 were obtained. Table 3 gives results obtained from tests made on cables for the purpose of localizing breaks in the North Atlantic, the Straits of Gibraltar, and the Mediterranean. Three of these were taken by a cable-ship staff, and three by shore staff. In no case was any correction for earth current necessary.

The "remarks" column in Table 3 refers to results calculated from the values of λ in the preceding column, which were calculated by means of the nomogram described on page 418.

Table 3

Name of cable	Value of m	Value of λ	Remarks
Mal-Ax 3	460	1·2	Result within 1 ohm
Car-Gt 1	500	1·2	Agreed with the accepted Lloyd test results
Car-Gt 1	410	1·2	
Car-Gt 1	510	1·2	
Pk-Gt 3	540	1·2	Error nil
Pk-Gt 4	240	1·3	Error −1 ohm

The considerable departures from the usually accepted Schaefer law that sometimes occur make it advisable to examine the results of tests to ascertain, if possible, what form of law is being followed. With large exposures, results tend to be high; with medium exposures results are usually good; while with small exposures results are often low. With very small exposures results are unreliable, though sometimes fair results are obtained with small currents.

Kennelly's Method

In this method, balances are taken to false zero so that the effects of all steady electromotive forces in the unknown arm are largely eliminated. A bridge measurement therefore gives the resistance up to the break plus the resistance of the end. The latter, according to Kennelly's law, varies inversely as the square root of the current passing through it, and it can thus be written as equal to $m/\sqrt{i}$, where i is the current in mA, and m is a suitable constant. The law was established in the first instance for balances taken to immediate false zero. In practice it is found to apply also to balances taken to the false zero observed after the interval which is imposed by the capacitance of a cable.

Two balances are taken with currents of ni and i mA, respectively. Then if B and A are the corresponding bridge readings,

$$x = B - (A - B)\frac{1}{\sqrt{n} - 1}$$

Thus the resistance x, in ohms, to the break can be determined. When n, the current ratio, is equal to 4 the formula reduces to $x = B - (A - B)$.

A graphical method is widely used. The procedure is similar to that described for the Schaefer test, except that in the present case balances are taken to false zero, and that values of $1/\sqrt{i}$ are used as ordinates. Suitably engraved scales are used both for the Schaefer and Kennelly graphs, so that balances can be plotted as quickly as they are taken.

Table 4

Estimated area	Value of m	Value of λ	Actual end resistance with 20 mA
sq. in.			ohms
0·30	76	2·15	20
0·20	98	2·15	24
0·12	140	1·97	31
0·11	177	1·85	35
0·10	190	1·94	41
0·07	257	2·14	62

Kennelly graphs show the following characteristics:—

(1) The graph for a large exposure has a greater slope than that for a smaller exposure.

(2) The result for a large exposure is a little high, for a medium exposure the result is correct, for a small exposure the result is low, and for a very small exposure the result in many cases again becomes high.

(3) The graph for a very small exposure tends to become steeper for the larger current values.

These characteristics are due to the fact that the law of end resistance varies with the size of the exposure, or, more precisely, with the current density at the exposure. The behaviour often observed when a very small exposure is tested with large currents is probably due to the inability of the hydrogen to escape freely from the copper because of bubbles adhering to the adjacent gutta-percha.

In one group of measurements made with the object of determining the law appropriate to various areas of exposure in sea-water the results shown in Table 4 (in

which the estimated area of exposure must be regarded as rough) were obtained.

The values in the Table were obtained by the method of least squares, using observations with currents between 5 and 20 mA. A further examination of the data obtained with currents not exceeding 10 mA gave for the last three exposures values of $\lambda = 1 \cdot 85$, $1 \cdot 85$, and $2 \cdot 1$, respectively, which suggested that by using smaller currents the tendency of λ to rise was delayed. Table 5 gives values of m and λ calculated from the data of

Table 5

Name of cable	Value of m	Value of λ	Actual end resistance with 20 mA
			ohms
Pk-Mad	120	1·78	22·5
Pk-Gt 3	252	1·59	37
Pk-Gt 4	194	1·98	43
Pk-Fy 1	204	1·61	32

localization tests made at Porthcurnow. The positions at which the ship had removed the breaks having been ascertained, a graph of the logarithm of the end resistance plotted against the logarithm of the current enabled the laws to be determined.

Correction of Kennelly Results.

There is a certain size of exposure, about $\frac{1}{3}$ sq. in. in area, which usually gives good results with all the standard tests. When the area differs considerably from this value there is a departure from the usually accepted laws, and a correction is necessary. The area of an exposure is necessarily unknown, but its relative value can be estimated from the slope of a Kennelly graph drawn from measurements made on it. The slope of the line can conveniently be expressed in terms of the end resistance with 20 mA, as shown by the graph, since this method of describing it is independent of the scales of the co-ordinates. The author has found the corrections given in Table 6 usually beneficial.

Table 6

End resistance by graph with 20 mA	Correction	Size of exposure
ohms		
10	− 2	Large
15 to 20	Nil	Medium
22 to 30	1 to 5	Medium to small

For end resistances of over 30 ohms the correction is unreliable. Provided that hydrogen is escaping freely the correction is an additional ohm for every 2 ohms above 30 in end resistance.

As will be seen later, strong earth currents affect the apparent end resistance, and though this may lead to incorrect information about the size of the exposures, the corrections may still be made with advantage. To illustrate the accuracy of corrected results, the r.m.s. value of the errors in 30 break tests taken in a laboratory on breaks having end resistances from 8 to 30 ohms was 1·4 ohms.

Effect of Earth Currents in the Kennelly Test.

When conductor resistance measurements are made on a cable in good electrical condition, the effect of steady earth currents is completely eliminated by balancing to false zero. It is not so, however, in break tests, for the behaviour of the end when the testing battery is withdrawn is altered by the presence of earth currents due to natural causes. The effect of an earth current acting in the same direction as the testing battery is to retard the rapid fall of the polarization e.m.f. when the testing battery is withdrawn, so that balances are lower than they would be in the absence of the earth current. The effect upon balances taken with large testing currents is small, but becomes greater with small testing currents. The earth current may be regarded as bringing conditions nearer to those existing when balances are being taken to reduced current zero. Alternatively, since the false zeros are read in the presence of a higher value of polarization e.m.f. than if there were no earth current, the balances are comparable with those in which the false zeros are read a little too

Table 7

	Balance to false zero with			End resistance by Kennelly test	Error in Kennelly result
	20 mA	10 mA	5 mA		
				ohms	
With 2 V assisting ..	17	23	32	15	+ 2
With no earth current	20	29	43	23	− 3
With 2 V opposing ..	24	35	51	27	− 3

soon after taking off the battery. The effect of an earth current acting in the opposite direction to the testing battery is to accelerate the fall of the polarization e.m.f. when the testing current is taken off, so that balances are greater than when there is no earth current.

The effects produced upon Kennelly graphs are as follows:—

(*a*) When the earth current assists the testing battery, it makes the end resistance at 20 mA, as shown by the graph, appear to be less, and tends to make the result high.

(*b*) When the earth current opposes the testing battery, it produces the opposite effects upon end resistance and result.

An idea of the magnitude of these effects may be gained from Table 7, which gives results obtained on an artificial exposure of about normal area. Tests were taken in the usual way, and then with a strong e.m.f. in the earth-return circuit.

Taking the Kennelly results as above, and applying the corrections indicated in Table 6, the final results would be + 2, − 2, and zero ohms, respectively.

With small exposures the effect of earth currents is much greater, making the application of corrections for them very difficult at times.

Bayard's Method

Measurements made by M. Bayard on artificial exposures, under conditions which allowed the free escape of hydrogen from the end, showed that for balances to immediate false zero the law appropriate to various areas of exposure was of the form $z = m/\sqrt[\lambda]{i}$, where λ had the values shown in Table 8. For areas of less than 0·02 sq. in., λ was 1·62.

Table 8

Area, sq. in.	0·08	0·16	0·32	0·48	1·6	3·2	4·8
Value of λ..	1·75	1·9	2·0	2·1	2·35	2·55	2·9

Faced with this variation, M. Bayard met the difficulty in a novel way. He proceeded to use the law for very small exposures ($\lambda = 1 \cdot 62$) for all sizes of exposure, and to calculate the correction necessary when the exposure did not obey the law assumed.

Now if an exposure is assumed to be obeying an inverse 1·62-root law, whereas it is in fact obeying the inverse λ-root law, and if B and A are the balances with ni and i mA, respectively,

$$x = B - (A - B)\frac{1}{\sqrt[\lambda]{n} - 1}$$

and

$$x = B - (A - B)\frac{1}{\sqrt[1\cdot 62]{n} - 1} - e$$

where e is the error arising when the wrong law is used. Therefore

$$e = (A - B)\left[\frac{1}{\sqrt[\lambda]{n} - 1} - \frac{1}{\sqrt[1\cdot 62]{n} - 1}\right]$$

In the case of a small exposure $(A - B)$ is large while the term in square brackets is small. For a larger exposure $(A - B)$ is smaller, while the other term is greater. The product therefore tends to vary within narrow limits, and the correction over a very large range of areas of exposure is practically constant. The amount of the correction is a function of the area of exposure and can therefore be related to the end resistance. The corrections necessary for various end resistances are shown in Table 9.

Table 9

End resistance at 20 mA, by graph	Correction
ohms	
$1\frac{1}{2}$	− 2
$1\frac{1}{2}$ to 30	− 3
31 to 40	− 2
41 to 60	− 1
Over 60	Nil

The practical procedure in the test is similar to that used in the Kennelly test, balances being taken to false zero with negative to line. The result may be obtained from a pair of balances, or from several balances by graphical means.

In the case of a graphical solution, values of $1/\sqrt[1\cdot 62]{i}$ are used as ordinates, and balances in ohms as abscissae. The best straight line is drawn through the plotted points. This line is produced, and the point where it cuts the horizontal axis gives the resistance (uncorrected) up to the break.

Bayard has established that the effect of experimental errors is least when the ratio of the currents in the two-current method is large, and therefore recommends a current ratio of at least 5 to 1. He recommends that the larger current be, if possible, 30 mA.

METHODS EMPLOYING BALANCES TO REDUCED CURRENT ZERO

In the case of balances taken on a break to true zero or to false zero, the end resistance is found, over a certain range of current densities, to conform to a law of the type $z = m/\sqrt[\lambda]{i}$. A graph of log z plotted against log i gives a straight line from which the value of λ can be found.

Table 10

Area	Zero read at 1 second		Zero read at 5 seconds	
	de	W	de	W
sq. in.				
0·91	84	6·8	96	6·1
0·49	103	7·5	109	7·4
0·28	108	8	114	8
0·19	103	9·7	114	9·4
0·07	100	12·6	102	13·1
0·055	100	14·6	105	15·0

When end resistances obtained from reduced current-zero balances are similarly plotted, a straight line does not result, indicating that a law of this type is not being followed. If. however, end resistances are plotted against the reciprocal of the current, the graph is linear, and is of a form corresponding to

$$z = de/i + W$$

where W is a constant depending upon the area of the exposure, i is the testing current in mA, and de is about 100 millivolts.

The graphs in Fig. 1 show the relation between the end resistance and the reciprocal of the current for several areas of exposure. The reduced current zero was read 1 sec. after reducing the current, that being about the time that would have been taken as the false zero interval. The values of de and W for the various exposures are shown in Table 10, which also includes the values obtained when the zero was read 5 sec. after reducing the current.

In Black's method, the earliest of those in which balances to reduced current zero were used, a formula of the type $z = de/i + W$ was assumed, and in Wald's modification of it de was taken as 100. In each of these tests

the value of W was taken as that applicable to an exposure of medium length.

In Lloyd's method an empirical formula is used which avoids the difficulty of estimating a suitable value for W.

Though objection may be taken on theoretical grounds to the formulae of Black, Wald, and Lloyd, the relative ease with which the tests may be carried out has led to their extensive use. Their usefulness, when applied with discrimination, has been amply proved in practice.

Black's Method

In this method, since measurements are made to reduced current zero, the effects of all constant electromotive forces in the unknown arm of the bridge are eliminated. The polarization e.m.f. at the exposure, however, does not remain unaltered when the current is reduced from its full value.

Black came to the following conclusions concerning the resistances and electromotive forces present at the end of a broken cable:—

(1) There is, at any particular exposure, a constant resistance which is unaffected by the polarization set up by negative currents. This resistance, W, is inversely proportional to the salt density and to the area of the exposure. For average values of these, W may be taken as equal to the conductor resistance of 1 nautical mile of core similar to that at the exposure.

(2) The polarization set up at the exposure increases slightly as the current is increased, until at 40 mA it reaches its maximum value. The e.m.f. of polarization varies in direct proportion to the 15th root of the current strength.

From (2) it follows that the e.m.f. of polarization present when the full testing current is flowing is greater

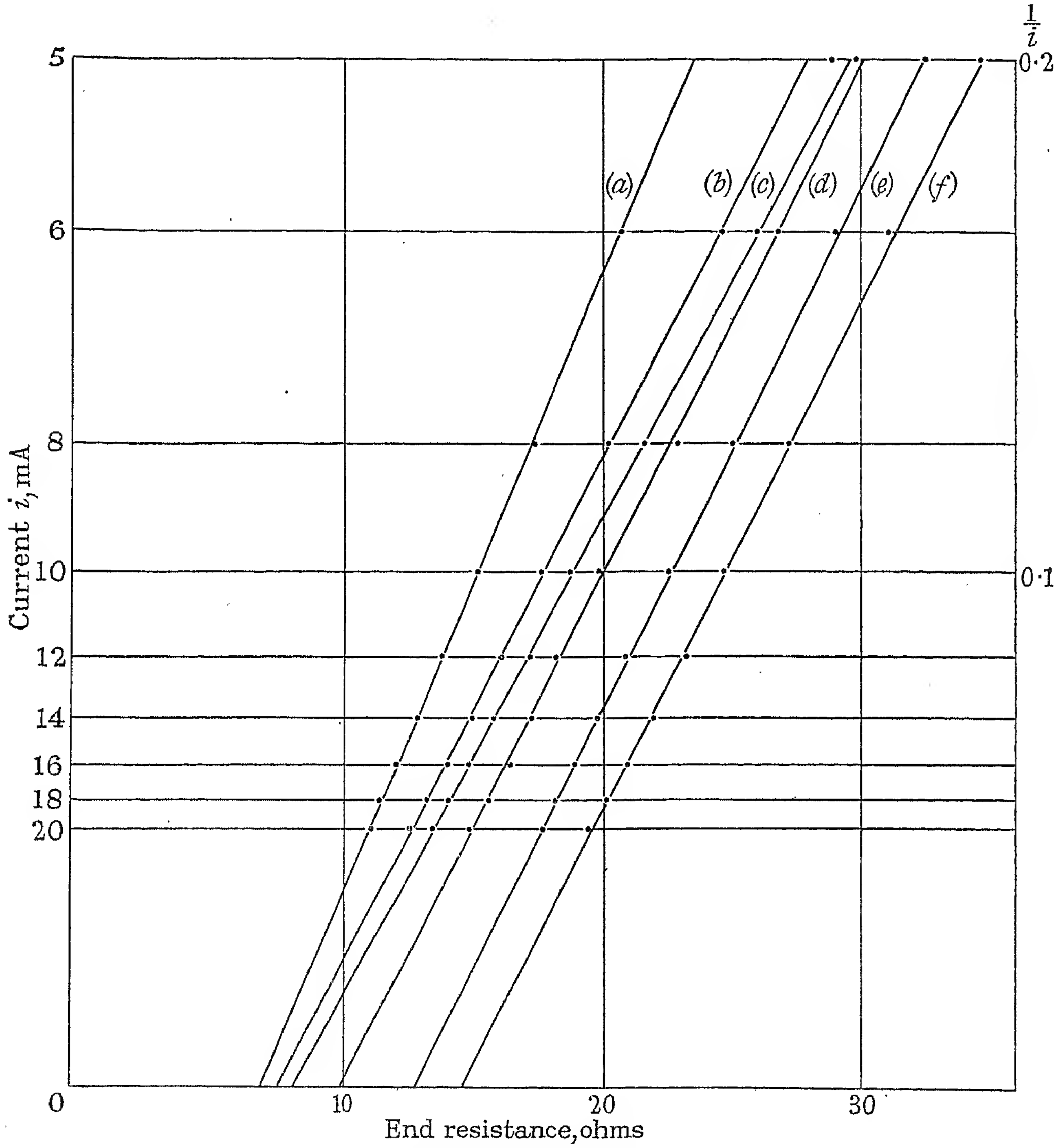


Fig. 1.—Graphs showing the relation between the reciprocal of the current and reduced-current zero balances for different areas of exposure.

(a) 0·91 sq. in.
(b) 0·49 sq. in.
(c) 0·28 sq. in.
(d) 0·19 sq. in.
(e) 0·07 sq. in.
(f) 0·055 sq. in.

than when the reduced current is flowing. The effect of this change is eliminated in practice by taking two balances to reduced current zero, the full currents being in the ratio of 2 : 1.

Then if B be the balance with $4i$ mA reduced to $2i$, and A be the balance with $2i$ mA reduced to i,

$$x = B - (A - B) - W$$

When the salt content of the sea-water differs from the average value of 3·5 %, and has a value of d %, then a constant W' is used, such that $W' = W(3 \cdot 5/d)$.

Wald's Method

Black's two-current test has generally been superseded by Wald's modification of it. Wald pointed out that the polarization error was in practice found to be equal to $100/i$ ohms, where i was the full testing current in mA, and that therefore one balance alone was necessary, and that the resistance to the break could be obtained from the formula

$$\begin{aligned} x &= B - (100/i + W) \\ &= B - (100/i + \text{C.R. per naut}) \end{aligned}$$

where C.R. stands for conductor resistance.

This test has been extensively used, and gives good results on a medium exposure. It suffers from the serious defect that the conductor resistance per naut is a suitable deduction only for a certain, though usually encountered, area of exposure, and that there is nothing in a one-current test to show that such an exposure is actually present.

It has been found that under laboratory conditions the following way of estimating the size of the exposure and of determining a corresponding suitable value of W gives good results when earth currents due to natural causes are absent.

The area of exposure may be considered as in the normal range if a Kennelly graph shows the end resistance with 20 mA to be between 10 and 30 ohms, and the difference between a false zero balance with 20 mA and a reduced current zero balance with 20 mA reduced to 10 is not greater than 10 ohms. When these conditions are satisfied, W may be taken as equal to the difference between the false-zero and reduced-current zero balances.

When these values are exceeded the exposure may be considered as small. With this condition, the test should be taken with 10 reduced to 5 mA, and W made equal to the difference between the false zero balance with 10 mA and the reduced current zero balance with 10 reduced to 5 mA.

It is sometimes said that a localization by Wald's method can be considered to be reliable when results calculated from measurements made with 20, 10, and 5 mA all agree. Agreement between such results proves only that the end is in a steady condition during the tests and that the exposure is not a very small one. Some measurements illustrating this point are given in Table 11. The conductor resistance per naut of the cable at the exposure was 7 ohms, and this value of W was used throughout.

In each of these there is a close agreement between the Wald results obtained with different currents for any particular exposure, but it is obvious that the result can not be called reliable solely on that account.

When the results on a certain exposure with these different currents do not agree, it can be taken that the exposure is very small or is behaving abnormally.

Lloyd's Method

In this method, measurements are made to reduced-current zero with currents of 20, 10, and 5 mA. The difference between the balances with 10 and 5 mA is compared with that between the balances wth 20 and 10 mA. When the ratio does not exceed 2 : 1 the exposure may be considered to be normal; when it is between 2 : 1 and 3 : 1 the exposure is small; when it exeeds 3 : 1 there is some abnormal condition at the end, in consequence of which tests will be unreliable while that condition lasts.

The balances obtained with the larger currents are used for normal exposures, and those obtained with the smaller currents are used for small exposures.

Table 11

Approximate area	Reduced-current zero balances with			Wald result			Mean error
	20 mA	10 mA	5 mA	1	2	3	
sq. in.							ohms
0·4	12	17	26	0	0	− 1	− 0·3
0·3	14	20	29	2	3	2	2·3
0·2	15	20·5	31	3	3·5	4	3·5
0·1	19	24	33	7	7	6	6·7

An appropriate pair of balances having been selected, the amount to be deducted for end resistance may be obtained from a table of coefficients given by Lloyd. If B is the balance with the larger currents, A the balance with the smaller currents, and d the difference between them, Lloyd gives the value of x as

$$x = A - dk$$

where k, the appropriate coefficient, is a function of d. Examination of the table of coefficients discloses the fact that k is a linear function of d, and that the formula can be written in the alternative forms

$$x = B - (2 \cdot 49d - 0 \cdot 02d^2)$$

and

$$x = A - (3 \cdot 49d - 0 \cdot 02d^2)$$

which have the advantage that the solution can be obtained without reference to the table of coefficients.

It is interesting to compare the above expression for end resistance with that used in the Kennelly test. In the latter, the end resistance is given in the form of $d/(\sqrt[\lambda]{2} - 1)$ for a 2 : 1 current ratio. If the Lloyd expression for end esistance be converted into this form it will be found that λ is a function of d, and that it has the values given in Table 12 for various differences.

For currents of 20 and 10 mA the first four correspond to large, medium, small, and very small exposures respectively, whilst the last is so small that accurate localization would probably be difficult.

An examination of the graphs in Fig. 1 shows that:—

(a) The ratio of differences over a wide range of areas of exposure differs very little from 2 : 1.
(b) The actual differences are approximately 5 and 10 for 5 out of the 6 exposures,
(c) When Lloyd's formula is applied, the best results for these various exposures are obtained when the balances used are those with 18 and 9, 20 and 10, 18 and 9, 16 and 8, 14 and 7, 10 and 5, and 8 and 4 mA, respectively.

To a greater degree than in other tests the accuracy of the result is dependent upon the current densities being within certain limits. To assist in the choice of suitable currents, Lloyd divides exposures into two classes according to the ratio of the differences. There are evidently intermediate cases where the best localization is obtained by taking the mean of the results obtained with the two groups of currents.

Table 12

d, in ohms	2·5	5	10	15	20
λ	2·0	1·97	1·9	1·83	1·75

The ratio of the differences is affected by variation of the end and by errors of observation to a greater degree in reduced-current zero balances than in the other types, because the end resistances are lower and because the sensitiveness of the balances is less.

The group of balances necessary for a Lloyd test should be taken several times, so that the figures finally selected may be characteristic of the exposure. It is to be remembered that a difference of 1 ohm in one of the balances may cause a wrong choice of balances and lead to an error of several ohms.

When, on account of the great distance to the break, one which should be tested with 20 and 10 mA can only be tested with 10 and 5 mA, the result is usually 3 to 4 ohms low.

Lloyd's Method of Correcting Mance's Test

Mance's test is one in which the effect of earth currents is eliminated in the measurement of the conductor resistance of a cable by taking two balances to true zero. The currents used are usually in the ratio of 2 : 1. Then, if the e.m.f. in the line is e millivolts, and B and A are the balances with currents of $2i$ and i mA, respectively,

$$B = x \pm e/(2i)$$
$$A = x \pm e/i$$

whence
$$x = B - (A - B)$$

When the method is applied to break tests, two sources of error arise, one due to the presence of the end resistance in the balances, and the other to the change in the value of the polarization e.m.f. when the current is changed.

In Lloyd's corrected Mance test, a deduction of $2 \cdot 41d$ is made from the ordinary Mance result, d being the difference between reduced-current zero balances with the same currents as are used in obtaining the true zero balances.

As in the Lloyd test, the relative size of the exposure is determined by the ratio of the differences between balances with 10 and 5 mA, and 20 and 10 mA. When the ratio is less than 2 : 1, the balances with the larger currents are used throughout; otherwise those obtained with the smaller currents are used.

The Determination of the "Law" during Tests

In view of the variations in the "law" observed with different exposures, it is important, if possible, to determine the law applicable to any particular exposure. Then, having determined the law, the correct deduction may be made for end resistance without any empirical correction. If, when the law is found, it is seen to be outside certain limits, then a warning is given of abnormal behaviour of the end.

Fig. 2 shows a nomogram which the author has devised to enable this determination to be made with the minimum of labour.

By its use one can read off

(a) The value of λ appropriate to the particular data.
(b) The value of end resistance $(A - B)\dfrac{1}{\sqrt[\lambda]{2} - 1}$.

The data required are reliable true-zero (if earth currents are absent) or false-zero balances with currents in the ratio of 4, 2, 1.

Let d_1 be the difference between the balances with 20 mA and 10 mA, and let d_2 be the difference between the balances with 10 mA and 5 mA.

Then if a straight-edge is put across the nomogram so as to connect the d_1 value indicated on the right-hand scale with the d_2 value on the left-hand scale, the value of λ is indicated by the intersection of the straight edge and the right-hand side calibration on the middle scale. Having determined the value of λ, lay the straight-edge so that the d_1 value is indicated on the right-hand scale, the value of λ on the left-hand side of the middle scale; then the deduction, $(A - B)\dfrac{1}{\sqrt[\lambda]{2} - 1}$, to be made from the balance with the largest current is indicated on the left-hand vertical scale.

When possible, at least three groups of differences should be used in determining λ, and the mean of the results used.

When over a certain range of currents a law outside the usual limits (for example, when for false-zero balances λ is not between 1·6 and 2·5) is indicated, then it is probable that a simple law is not being obeyed throughout that range, and another range of currents should be tried instead. Alternatively the end may not be in a clean condition and may, after further testing, give satisfactory results later with the same range of currents.

The localizations in Table 3 were all calculated by means of the nomogram when examining the data of the tests at a later date. In five cases out of the six the results were better than those obtained by the Schaefer graph method.

The nomogram is not suitable for use with reduced-current zero balances. These, over the required range of currents, do not usually conform to the type of law for which the nomogram is designed.

With false-zero balances, when the differences are small, errors of observations considerably alter the apparent value of λ, so that careful measurements are necessary. With smaller exposures the differences are greater and the effect of errors of observation is not so great.

The construction of the nomogram depends upon the assumption that the end resistance varies inversely as the λ root of the current.

Then $d_2/d_1 = \sqrt[\lambda]{2}$ and $\log d_2 - \log d_1 = 0 \cdot 301/\lambda$

Since this equation is of the form $u - v = w$, it can be solved by means of a suitable nomogram in which the subdivision of the outer scales (u and v) is logarithmic.

The amount to be deducted for end resistance from the balance with the largest current is

$$z = d_1/(\sqrt[\lambda]{2} - 1) = kd_1$$

Then $\log z - \log d_1 = \log k$

This equation is of the same form as the one used above, and may also be solved by means of a nomogram. All the scales for this must be logarithmically calibrated. The scale of d_1 can be used again, and the values of z can be read off from the scale of d_2, provided that a suitable logarithmic scale of k be placed in the middle.

It has been pointed out by A. L. Barlow that, when the intermediate step of finding the value of λ is not considered necessary or helpful, the deduction may be obtained directly from the formula

$$z = (d_1)^2/(d_2 - d_1)$$

provided that d_1 and d_2 themselves are not small.

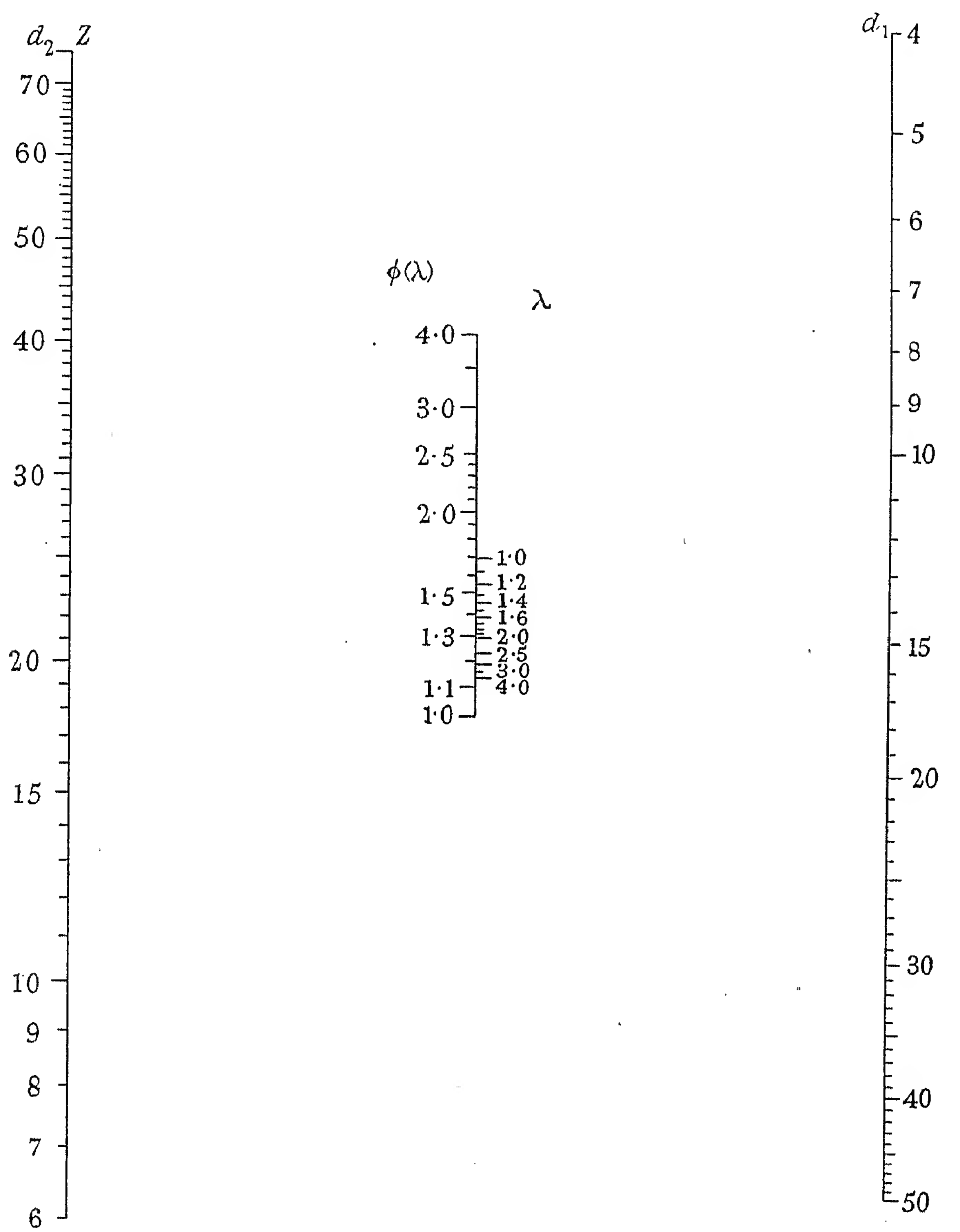


Fig. 2.—Nomogram for use in break tests.

Small Exposures.

When the exposed area is small, the accurate localization of a break presents some difficulties that are not met with in the more usual size of exposure. There is a tendency to depart from the usual laws, there is often unsteadiness of resistance, and the balances are more affected by earth currents.

The main indications of a very small exposure, having an area of $0 \cdot 05$ sq. in. or less, are

(1) The end resistance at 20 mA by Kennelly test is greater than 30 ohms.

(2) The difference between false-zero and reduced-current zero balances with 20 mA is between 10 and 20 ohms (in the absence of strong earth currents).

(3) The ratio of differences in reduced-current zero balances with 5, 10, and 20 mA is greater than 2 : 1.

(4) The time during which the Lumsden balance is at its minimum is very short and is not more than 1–2 sec. The minimum balance is 20 or 30 ohms above the result by Kennelly graph.

(5) The " law " of the end, as given by nomogram, is abnormal.

It is not possible to give firm rules about the behaviour between false-zero and reduced-current zero balances with 10 mA, provided that the earth current is small.

With Kennelly graph end-resistances of over 60 ohms with 20 mA, only a very careful study of all available information, and some experience, will enable even a fair localization to be made.

EXAMPLES OF TESTS

Table 13 gives examples of balances and results on artificial exposures for the range over which accurate results are usually obtainable. The areas were of the order of $0 \cdot 6$, $0 \cdot 3$, $0 \cdot 15$, and $0 \cdot 1$ sq. in. respectively. In this small number of examples the Lloyd–Mance test gives low results. An examination of a large number of results for exposures of similar areas does not, however, show the apparent tendency to lowness. The Schaefer and Kennelly results were obtained graphically, using a larger number of balances than are shown in the Table.

The following is an example of a test which, though exceptional in the consistency of the results, illustrates the behaviour observed under favourable conditions on a very small exposure. The balances were unsteady, so that the mean of five groups of balances was taken.

Table 13

True-zero balances with			False-zero balances with			Reduced-current zero balances with			Results of tests							
									Schaefer	Kennelly		Bayard	Wald	Lloyd	Lloyd-Mance	Lumsden
20 mA	10 mA	8 mA	20 mA	10 mA	5 mA	20 mA	10 mA	5 mA		Un-corrected	Corrected					
24	42	50	10	14	19	8	12	19	0	1	− 1	0	− 1	− $1 \cdot 6$	− $3 \cdot 6$	4
35	60	70	18	$25 \cdot 5$	36	12	17	25	0	0	0	1	1	0	− 2	5
34	58	67	22	—	50	14	19	30	0	− 6	− 2	− 2	1	2	− 2	10
39	58	—	25	36	52	15	21	30	7	− 2	1	2	0	1	− 4	—

of such exposures during tests, but the following observations will usually be helpful in co-ordinating the results of various tests.

The Kennelly graph made from balances taken with currents over the full range up to 20 mA gives unreliable results with small exposures. The tendency which such a graph shows—to give low results when the exposure is small—is often reversed with exposures of less than $0 \cdot 05$ sq. in. Then instead of the graph giving a result that might be expected to be 5–10 ohms low, it is as many ohms high.

The Bayard graph for very small exposures gives higher results than the Kennelly graph, so that when abnormal behaviour causes the Kennelly graph to give high results the Bayard graph gives still higher results.

Decidedly better results are in each case obtained with currents not exceeding 10 mA, despite the reduced sensitiveness of the balances with smaller currents.

In Lloyd's method small exposures tested with small currents give very fair results, but with very small exposures the result is usually high.

In Wald's method, a fair result is often obtained when the reduced-current zero balance with 10 reduced to 5 mA is used, and W is made equal to the difference

The false-zero balances were:

16 mA; 52 ohms
8 mA; 80 ohms
4 mA; 122 ohms
12 mA; $62 \cdot 5$ ohms
4 mA; 122 ohms.

If Kennelly's law is applied to these figures, an end resistance of 60 ohms at 20 mA is shown (and an error of − 18 ohms). This is so large that it is far outside the range in which a correction can be applied.

Applying Bayard's formula to the 16-mA and 4-mA balances,

$$x = 52 - (52 \cdot 5 + 1) = - 1 \cdot 5$$

and to the 12-mA and 4-mA balances,

$$x = 62 \cdot 5 - (59 \cdot 5 + 1) = 2$$

The mean of these gives the correct result.

By nomogram the law is $\lambda = 1 \cdot 7$, and the mean of two results is $- 3 \cdot 5$.

The true-zero balances were 61, 97, and 155 ohms with 16, 8, and 4 mA respectively. By nomogram the law is $\lambda = 1 \cdot 47$, whence $x = 1$. A Schaefer graph drawn from a larger number of observations gave $+ 9$ ohms.

The reduced-current zero balances were 20, 28, and 46 respectively. As the ratio of the differences was greater than 2 : 1, the balances with the smaller currents were used, giving a result of -10 by Lloyd's method. It is to be noted that the correct answer would have been obtained if the balances with the larger currents had been chosen.

CONCLUSION AND ACKNOWLEDGMENT

If one break test could be relied upon always to give the correct result, then all others would at once become obsolete. But the range of areas of exposure, and the variety of physical conditions at the end, make this impossible. When the results by different methods do not agree, the knowledge of a formula is evidently not sufficient. A careful study of the behaviour of the break under different testing conditions is necessary, together with the application of knowledge which can only be partially obtained without considerable experience.

The usefulness of the various tests may be summarized as follows:—

True-zero balances are easily and quickly taken. In the absence of earth currents the methods described are capable of giving good results. When strong earth currents are present, large corrections to the observed balances are necessary, and accurate results are only obtainable when the earth current is steady throughout the test.

False-zero balances are less easy to take, particularly on very long lines. Corrected Kennelly graphs give good results so long as the correction is small. Corrected Bayard graphs give good results over the same range of exposures. The usefulness of the latter, however, extends to smaller exposures under favourable circumstances.

Reduced-current zero balances are much easier to take than false-zero balances, and the deduction for end resistance is smaller than with other kinds of balance. The simplicity of Wald's test makes it suitable for obtaining a quick result, but the arbitrary deduction of the resistance per naut is a theoretical weakness, which can to some extent be removed if the deduction is based on the behaviour of the end. Lloyd's test gives good results with large and medium exposures. With smaller exposures it gives good results if the correct currents are used, but it is more critical in respect of the currents used than are other tests.

The author desires to express his thanks to Cable and Wireless, Ltd., for giving permission for the production of this paper.

BIBLIOGRAPHY

A. E. KENNELLY: "The Resistance of Faults in Submarine Cables," *Journal of the Society of Telegraph Engineers*, 1887, vol. 16, p. 219.

C. W. SCHAEFER: "A New Method of localizing Total Breaks in Submarine Cables," *Electrician*, 1897, vol. 39, p. 811.

R. R. BLACK: "The Reduced Current Method for localizing Fractures in Submarine Cables," *ibid.*, 1910–11, vol. 66, p. 1038.

G. WALD: Correspondence relating to Black's test, *ibid.*, 1911, vol. 67, p. 66.

J. F. LLOYD: "Notes on the Localization of Breaks or Faults in Submarine Cables," *ibid.*, 1919, vol. 83, p. 498.

M. BAYARD: "The Localization of Breaks in Submarine Cables by False Zero Measurements," *Annales des P.T.T.*, 1933, vol. 22, p. 497.

D. K. MCLEERY: "Submarine Cables: Testing in the presence of Earth Currents in a Laid Cable," *Electrician*, 1933, vol. 111, p. 583.

APPENDIX

Wheatstone-Bridge Formulae for Reduced-Current Zero or False-Zero Balances

(1) Steady e.m.f. in the unknown arm.

When a balance to reduced-current zero is obtained, the current in the cross-circuit is the same with the full e.m.f., E_1, applied and with the reduced e.m.f., E_2, applied to the bridge. The applied voltage may be reduced to any value in order to obtain the "zero" deflection, though in practice the reduction is such that the current to line is halved. When the applied e.m.f. is reduced to zero we have the conditions for reading the usual false-zero deflection, so that a balance to false zero may be regarded as a particular case of the reduced-current zero balance.

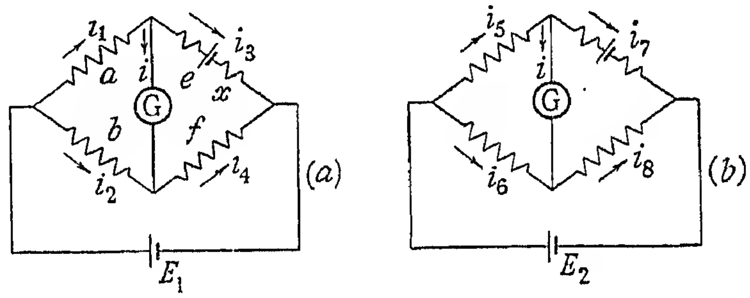


Fig. 3

Let Fig. 3(*a*) represent the conditions when the full voltage is applied, and Fig. 3(*b*), the conditions when the voltage is reduced. Let the currents be as shown. When balance is obtained, the current in the galvanometer is the same in the two cases.

Then, applying Kirchhoff's laws,

$$\left.\begin{aligned} ai_1 + iG - bi_2 &= 0 \\ ai_5 + iG - bi_6 &= 0 \end{aligned}\right\} \quad \left.\begin{aligned} xi_3 - fi_4 - iG &= -e \\ xi_7 - fi_8 - iG &= -e \end{aligned}\right\}$$

Therefore

$$\frac{a}{b} = \frac{i_2 - i_6}{i_1 - i_5} \quad \text{and} \quad \frac{x}{f} = \frac{i_4 - i_8}{i_3 - i_7} \quad . \quad . \quad (1)$$

$$\left.\begin{aligned} i_1 &= i + i_3 \\ i_5 &= i + i_7 \end{aligned}\right\} \quad \left.\begin{aligned} i + i_2 &= i_4 \\ i + i_6 &= i_8 \end{aligned}\right\}$$

whence

$$\frac{i_2 - i_6}{i_1 - i_5} = \frac{i_4 - i_8}{i_3 - i_7} \quad . \quad . \quad . \quad . \quad (2)$$

Comparing (1) with (2), it follows that $a/b = x/f$, and that the usual bridge balance relation holds good. Since no limitation has been placed upon the value of E_2, it follows that the proof is valid for both reduced-current zero and false-zero balances.

(2) When the e.m.f. in the unknown arm includes a variable component.

This is of importance when, owing to the fall in the polarization e.m.f. when the full testing current ceases, a

reduced value of e.m.f. acts in the unknown arm while the zero is being observed.

Let the e.m.f. in the unknown arm be e with the full current, and $(e - de)$ with the reduced current.

Then, as before,

$$\frac{a}{b} = \frac{i_2 - i_6}{i_1 - i_5} = \frac{i_4 - i_8}{i_3 - i_7}$$

Now, however,

$$xi_3 - fi_4 - iG = -(e)$$
$$xi_7 - fi_8 - iG = -(e - de)$$

So that

$$x(i_3 - i_7) - f(i_4 - i_8) = -de$$

and

$$x = f \cdot \frac{i_4 - i_8}{i_3 - i_7} - \frac{de}{i_3 - i_7}$$
$$= f\frac{a}{b} - \frac{de}{di}$$

where di is the change in the current in the unknown arm.

In the case of a false-zero balance taken with a large current, i_7 is very small compared with i_3, and x is approximately equal (with the usual even bridge ratio) to $(f - de/i_3)$, i_3 being the testing current to line.

There is a certain inevitable drop in the polarization e.m.f. at a break before the false zero can be read. Thus there is a small error, the value assigned to x being too great. If, owing to difficulty in choosing the proper false-zero interval, the observation of the false-zero is delayed still longer, de is greater, and the error is greater. With large currents the error is only 2–3 ohms. With small currents $(i_3 - i_7)$ is much smaller, so that the error, $de/(i_3 - i_7)$, is much greater.

Suppose that in the course of a series of balances on a normal exposure the false-zero interval has been made too great. All balances will be incorrect, the error with small currents being greater than that with larger currents. A Kennelly graph drawn from these balances will have too small a slope, and the end resistance with 20 mA, as read on the graph, will be greater than it ought to be for that size of exposure. When such an error is made the graph gives a low result, but the error is to a large extent eliminated when the correction indicated in Table 6 is applied. The correction is of the right sign for the purpose, but it is not necessarily of the right value. Table 14 shows the effect upon the balances of delaying the observation of the false zero when testing on a normal exposure. Kennelly graphs drawn from the data gave $-0 \cdot 5$, $-4 \cdot 5$, and $-9 \cdot 5$ ohms, with end resistances of 18·5, 27·5, and 35·5 ohms, respectively. The first would require no correction, the second would usually be corrected by adding 3, whilst the last is in the range in which the correction is considered to be unreliable. On the other hand, Bayard graphs drawn from these data gave end resistances that were all under 30 ohms with 20 mA, requiring, therefore, a constant correction of -3 ohms. The corrected Bayard results were 1·5, $-1 \cdot 5$, and -2 ohms, respectively. Thus the errors in the corrected results are much smaller than might be expected from the effects upon the individual balances.

Table 14

Current	Balance with false zero read		
	Correctly	2 seconds late	5 seconds late
mA	ohms	ohms	ohms
20	18	23	27
16	20	25	30
10	25	34	41
8	28	38	46
5	36	51	62
4	41	58	73

Nomogram for calculating values of coefficients

A nomogram is a convenient means of obtaining the values of the coefficients $k = 1/(\sqrt[\lambda]{n} - 1)$ for various values of n and λ. Such a nomogram is shown in Fig. 4. When a straight edge is joined between selected values of n and λ, the value of k is read off where the straight edge cuts the scale of k.

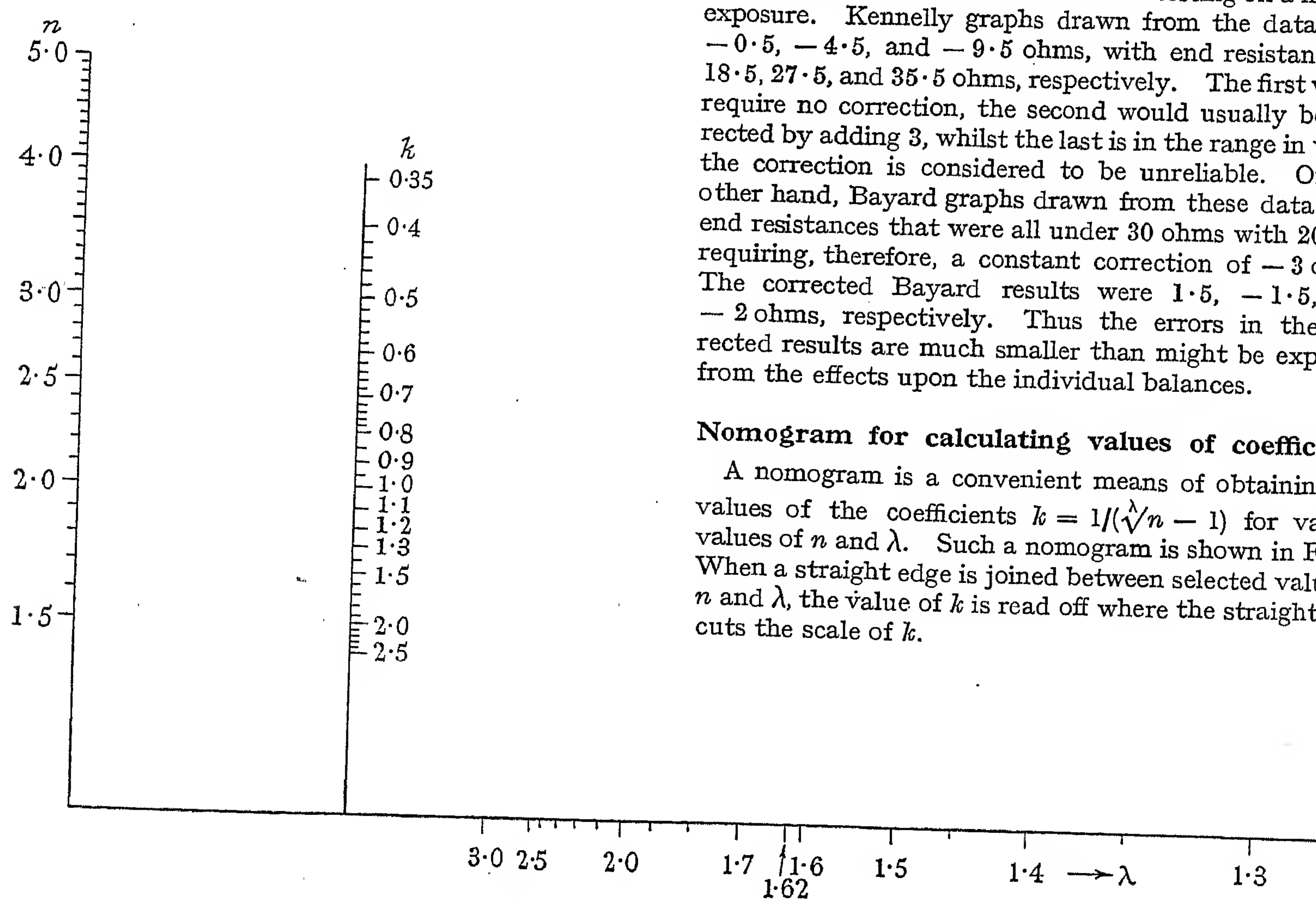


Fig. 4.—Nomogram for finding value of $k = \dfrac{1}{\sqrt[\lambda]{n} - 1}$

ROSENBERG DYNAMO WITH FIXED POLARITY*

By DR. E. ROSENBERG, Member.

(*Paper first received* 10*th December*, 1938, *and in revised form* 15*th February*, 1939.)

SUMMARY

The design, construction, and experimental data, of a generator are shown which, while retaining the properties of the Rosenberg cross-field design, ensure fixed polarity by means of a permanent magnet and magnetic shunt. The field and mechanical parts of the machine are of welded mild steel, the only cast part being the permanent-magnet bar. The drooping part, the peak part, and the no-load point, of the current/voltage curve are discussed and the small influence of the regulating pole setting on the no-load voltage is explained. The result of paralleling two machines without an equalizing bar is that one machine is generating and the other, with lower setting of the regulating pole, is motoring with temporarily reversed field. After disconnecting, the correct polarity is re-established owing to the action of the fixed pole. The fixed-pole design can also be used in ordinary plant for exciters.

INTRODUCTION

The cross-field machine, invented by the author in 1904, was then used for train lighting only.† During the following years it was applied to some extent to welding.‡ Since the introduction of the regulating pole it has found a huge field of application in electric arc welding.§ Since then many makers in Europe and America, also in England, have built similar machines, embodying the features of the old cross-field machine and trying to achieve the necessary regulation in other ways. The principle of the machine may be stated in a few words. In a 2-pole generator the ordinary brushes are short-circuited and serve as auxiliary brushes to create by armature reaction a secondary field (the transverse or cross field) which induces in the armature conductors a voltage with a maximum at points midway between the auxiliary brushes. At these points the main brushes are installed. The tertiary field caused by the armature reaction of the main current is in direct opposition to the primary field. The voltage of the main brushes is independent of the direction of rotation, because with the reversal of the latter the secondary field also reverses. The machine, as made in the beginning of the century for train lighting, had shunt or battery excitation.|| As a small difference between primary and tertiary fields is sufficient to induce the small voltage required to send the necessary current through the armature, short-circuited by means of the auxiliary brushes, the main armature current automatically reaches such a value that for any but the lowest speed the tertiary field nearly equals the primary field. For a wide range of speeds and external resistances the machine is a constant-current machine. For welding and feeding arc lamps (searchlights and cinema projectors) the machine was made with restricted pole section and series excitation, giving moderate no-load voltage and a drooping characteristic over a wide range of current. The series excitation increases the voltage with increasing current only as long as there is no high saturation in parts of the field structure. With further increasing current the growth of the primary field is limited, while that part of the opposing tertiary field which sends its flux through the air still continues to increase. In consequence, the resultant field is reduced with increasing current. By proper choice of shape and section of the saturated parts, by far the greatest part of the current/voltage characteristic can be made drooping.

DESIGN

The latest form of the dynamo is shown in Figs. 1 and 2. The upper pole of the field structure is the regulating pole (Fig. 3) by means of which the welding or arc-lamp current is varied during operation. The lower pole, which we may call the "fixed pole," fulfils two functions. The first of these is to adjust the machine on the test-bed to compensate for individual slight differences, so as to be able to use the same dial of the regulating pole for every machine (Fig. 4). The other important function is to secure the same polarity, even if a machine has been subjected to strong reverse currents owing to its being wrongly connected, either while stationary or when running, to another machine of higher voltage.

Both in Fig. 1 and in Fig. 5, the diagram of connections, the brushes are shown as though the commutator bar were in line with the armature wire to which it is connected. The main brushes BB are situated in the centre line of both the main poles and commutating poles CP, while the auxiliary brushes "bb" are situated in the same position as the brushes of a conventional machine, i.e. in the neutral zone between the pole shoes, and, being short-circuited, allow an internal flow of current in the armature conductors, thus permitting different values of the current in the 4 quadrants of the armature winding. These brushes carry a small current under all conditions of load and have only half the section of the main brushes BB.

The "regulating pole" (Figs. 1, 2, and 3) consists of an outer shell with circular openings or "windows" W and an inner piston S (Fig. 2) that can be moved lengthways by means of a flat-threaded screw F. Less than one turn of the handwheel H suffices for this. A dial (Fig. 4) indicates the current corresponding to each position of a knob on the handwheel serving as a pointer.

* The Papers Committee invite written communications, for consideration with a view to publication, on papers published in the *Journal* without being read at a meeting. Communications (except those from abroad) should reach the Secretary of The Institution not later than one month after publication of the paper to which they relate.

† See Reference (1). ‡ *Ibid.*, (2). § *Ibid.*, (3). || *Ibid.*, (4).

An outer scale is used for heavy currents, and an inner scale for small currents. The smallest iron section, represented by the material left between the windows of the outer shell, is not more than about 4 % of the full section of the piston.

The " fixed pole " (Figs. 1 and 2) is a combination of a straight permanent magnet and a magnetic shunt, constructed of mild-steel parts with an air-gap between them. The permanent magnet, PT, cast in the form of a tube with a centre opening and marked in

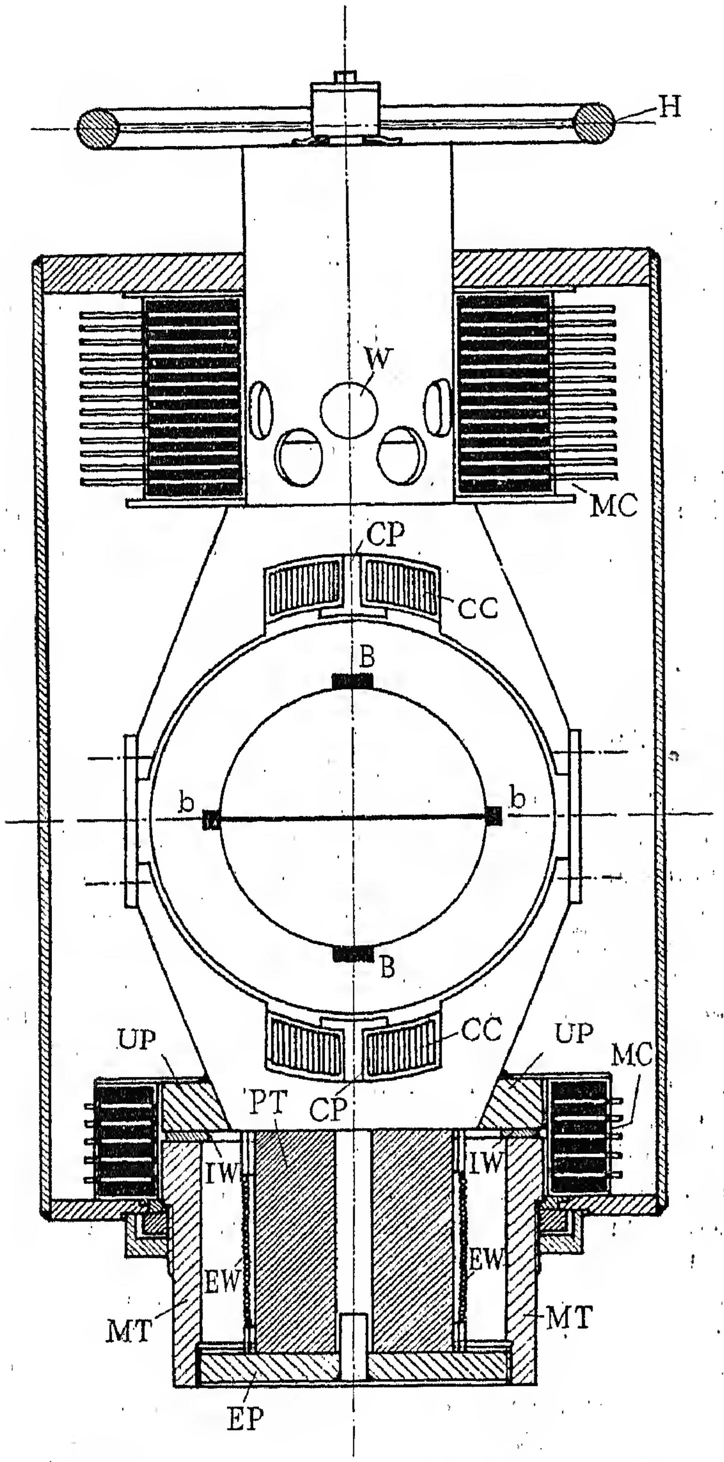


Fig. 1.—Cross-section through the generator.

Figs. 1 and 2 by heavy shading, is of sufficient section and length to send through the armature, when the electric circuit is broken, such a flux that correct polarity results even if a reversed current, sent through the machine, has reversed the polarity of the mild-steel parts of the field structure. But the permeability of the material used for the permanent magnet is low and, although its section is nearly equal to the full section of the regulating pole, it is by no means sufficient to carry all the flux necessary for working with full-load current. The magnetic shunt provides the necessary section for this purpose. It is composed of an outer mild-steel tube MT, two mild-steel end plates, UP and EP, and a non-magnetic washer IW (the " air-gap ") between the upper plate UP and the outer shell MT. The magnetic shunt diverts the reversed flux, if the machine is wrongly paralleled, in a harmless way, i.e. with a value of magnetic potential that is much lower than the coercive force of the permanent magnet.

The commutating coils CC and the main exciting coils MC (which latter are provided with cooling fins) are coaxial and are connected in series with the main brushes BB and with the outer circuit (Fig. 5). The characteristic curves are not appreciably altered by the addition of the permanent magnet. The curve in Fig. 6 is drawn for the " full in " position of the regulating pole and has the same shape as those of machines with mild-steel field structure throughout,* showing 40 volts at no load and a rising part with a peak of 80 to 90 volts, when the current is about one-fifth of the maximum. From this point the drooping part of the characteristic starts and with zero voltage the current reaches its maximum, which is less than 20 % in excess of the current corresponding to an arc voltage of 30. Short-circuit and open-circuit running, and running on peak voltage, do not unduly strain any part of the machine, and all parts of the characteristics can be used for permanent operation with the proper time factor.

Drooping Part of the Current/Voltage Curve

Voltages as low as 15 and as high as 60 may be required for welding. Bare or slightly dipped steel electrodes require from 15 to 25 volts; heavily coated steel electrodes, cast-iron electrodes, carbon electrodes for welding iron, and carbon electrodes for welding copper, require progressively higher voltages. The machine can be used for all these purposes and its performance is little affected by an extra length of cable providing additional resistance, as often happens in odd jobs. Tangents to the curve (Fig. 6) at the points corresponding to 20 and 40 volts, marked t_{20} and t_{40}, cut the vertical axis at 175 and 150 volts. This very important part of the static characteristic corresponds to that of a machine with a straight-line characteristic and more than 150 volts no-load voltage, although here the no-load voltage is low.

For large arc lamps a voltage of 60 to 80 is required. Where higher speed of the driving motor is permitted, the standard armature of the welding generator can be used also for searchlights without change of winding.

Peak of the Curve

The part " h " in Fig. 6, adjacent to the peak of the curve, gives nearly constant voltage for a range of current of 8–35 % of the maximum. Also this part can be applied usefully, e.g. for supplying, in the intervals of welding, current to d.c. motors for grinders or other tools, and for illumination. The motors or incandescent lamps are chosen for the peak voltage of the highest curve with the regulating pole full in, to make sure that under no condition can the tool motors be overspeeded or the lamps overrun. In exceptional cases when it is desired to make small welds with very thin wire from a big machine

* See Reference (5).

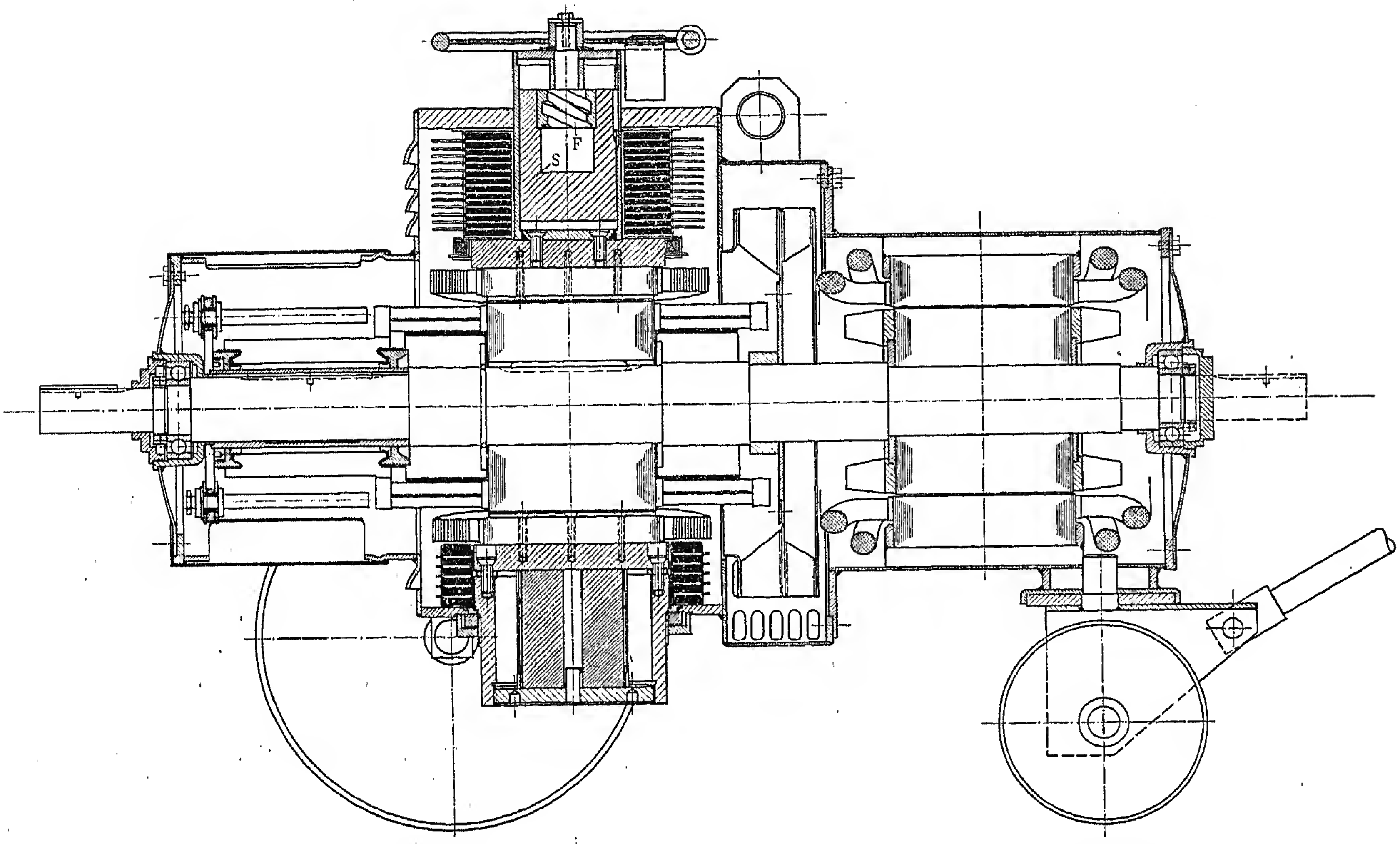


Fig. 2.—Longitudinal section through portable welding generator and 3-phase driving motor.

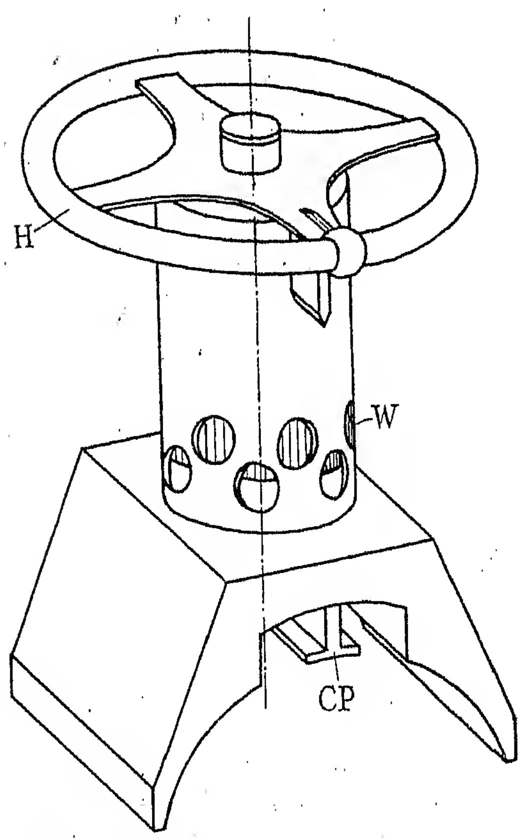


Fig. 3.—View of regulating pole, pole-shoe, and commutating pole without coils.

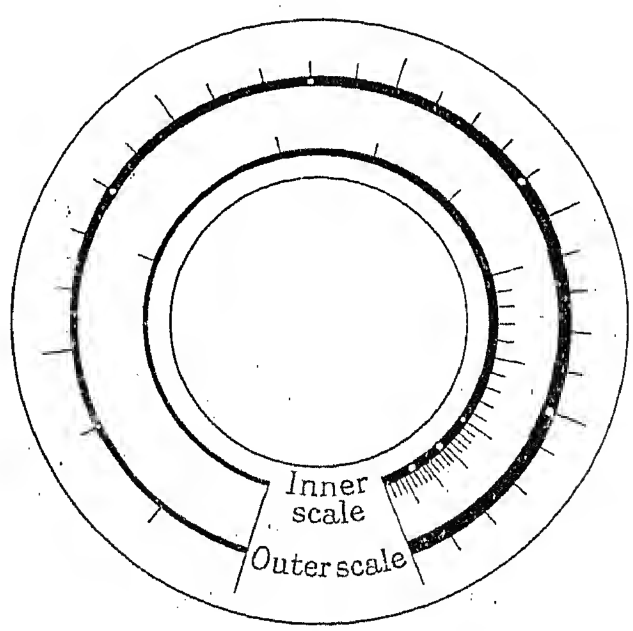


Fig. 4.—Dial of regulating pole.

normally used for heavy work, it is possible to work several small arcs in parallel on the peak voltage with ballast resistances in the same way as from a multi-operator constant-voltage machine.

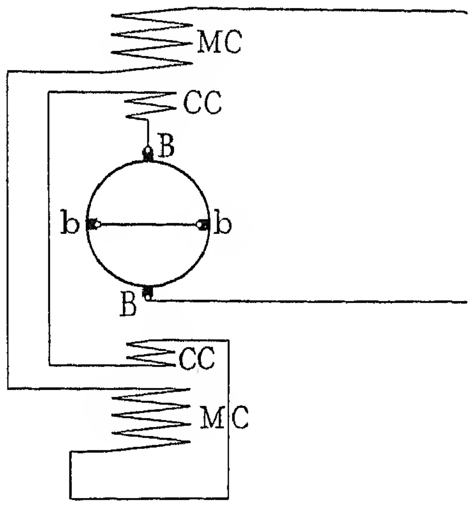


Fig. 5.—Diagram of connections.

In Fig. 7 two curves and in Fig. 8 ten curves are shown, corresponding to various positions of the regulating pole. The position of the regulating pole influences not only the short-circuit current but, to a lesser degree, also the peak voltage. The regulating-pole handle may therefore be used for reducing the voltage when working on the peak of the curves.

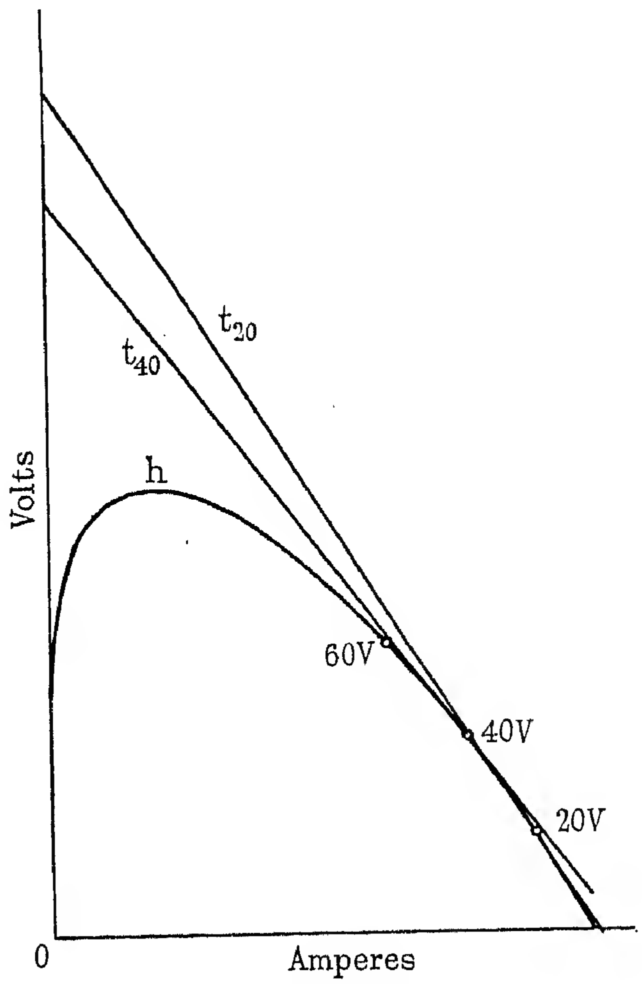


Fig. 6.—Current/voltage curve.

Open-Circuit Voltage

The open-circuit voltage is of importance to the dynamic characteristic and also from the point of view of the operator's safety. The rush of current at the moment of short-circuit, when welding starts, is determined by the open-circuit voltage and the impedance of the circuit, and is therefore at 40 volts only one-quarter of what it would be at 160 volts with the same impedance. As to safety, the ordinary working voltage is low, and

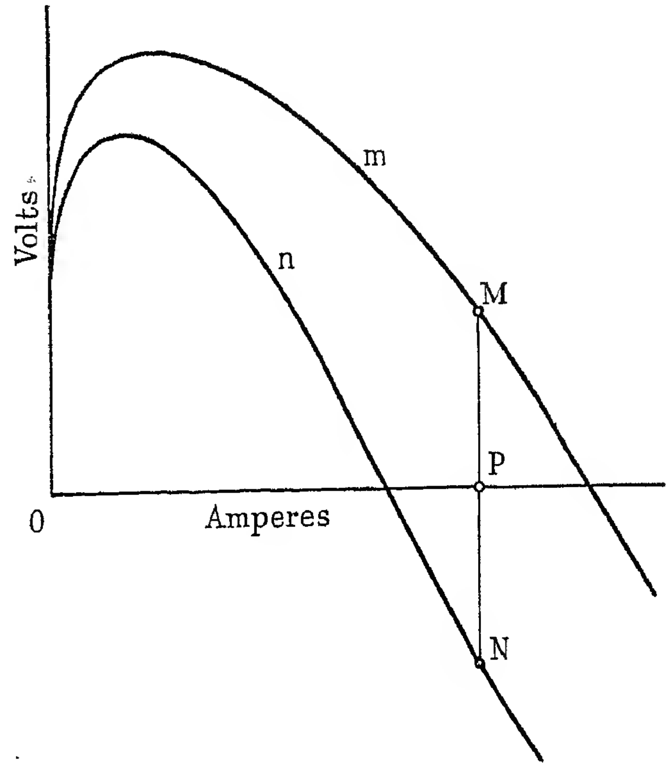


Fig. 7.—Curves for two different settings of the regulating pole. Resulting current when connected without equalizer.

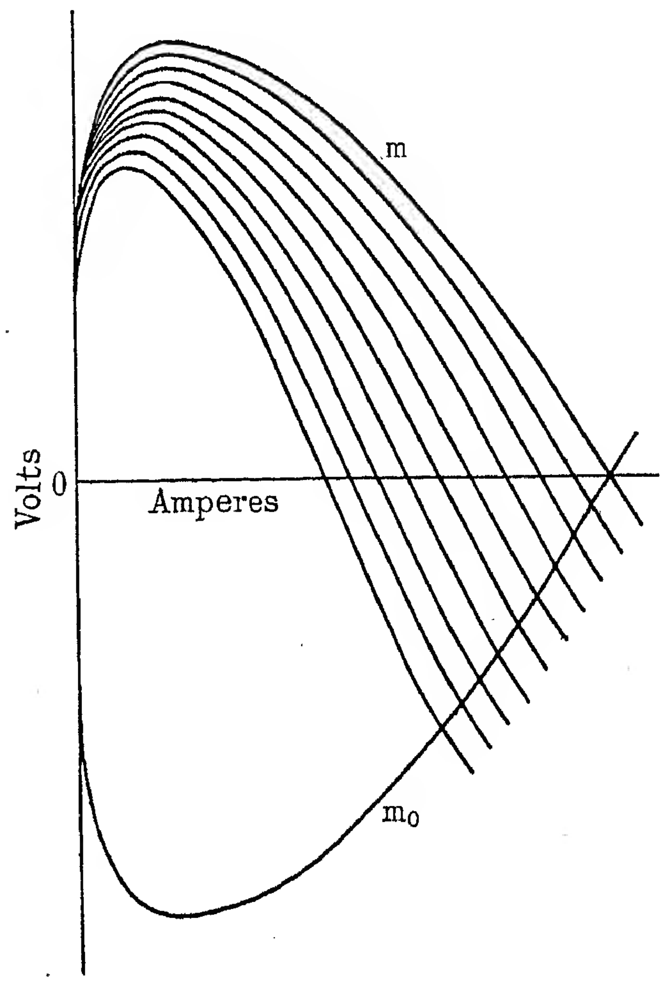


Fig. 8.—Curves for 10 settings of the regulating pole.

the peak voltage, that occurs just before breaking the arc, is of such short duration that it is not dangerous, just as a finger moved rapidly through a flame is not hurt in spite of the high temperature of the flame. But the open-circuit voltage is of the greatest importance. The memorandum of the Factory Department of the Home Office on electric arc welding points out that the chief risk to the operator lies in renewing or adjusting the electrode in the holder while repair work in a boiler or other akward situation is going on. Although direct current for such work is in general preferable to alternating, a small no-load voltage affords complete safety.

It is one of the most puzzling features of this machine that the voltage of the unexcited machine should vary so little with the setting of the regulating pole, although the iron section available for the primary flux may be varied in the ratio of 100 : 4. But if the residual magnetism, as in a conventional machine, is 1–2 % or even 3 % of the full field, then the iron is not highly saturated, even if the section is reduced to 4 %, and therefore the increased reluctance of the poles does not reduce the residual magnetism so much as one is led to believe. On the other hand, 1–3 % of the field induces a voltage in the armature sufficient to send a fraction of the full-load current through the short-circuited brushes; and the cross field through armature iron and pole shoes set up by this current gives sufficient voltage between the main brushes.

Experimental Design

The form of machine shown in Figs. 1 and 2 has been adhered to, although other forms are possible and have been tried experimentally. Fig. 9 shows a form without salient poles, built and wound in the manner of an induction motor or rather of a compensated commutator machine with only a compensating and a commutating winding, the former having slightly more effective turns than the armature. The stator windings are distributed in the slots of the two pole-shoes which form the greatest part of the stator, two thin bridges between the pole shoes representing the highly saturated path with variable section. Here also can be placed the permanent-magnet plates with magnetic shunt. A distributed winding, on the one hand, requires more turns than a winding concentrated on a pole limb, but this is countered on the other hand by the reduction of the leakage between the field and the armature windings. It was of theoretical interest to investigate whether this entirely different form would give the same kind of characteristics, and it did so in fact. The two important factors, leakage and saturation, can be properly exploited also with this shape of field structure, resulting in the same general shape of characteristic curves. But although the form may be of advantage in reducing the outside diameter of the machine to the smallest possible limit, it does not seem to represent advantages from the economical or manufacturing point of view. It has been found preferable to standardize the design with two salient poles and to put the permanent magnet with its magnetic shunt only on the "fixed" pole.

Alternatives to the Fixed Pole

Long ago such machines were fitted with a small separately-excited field winding that fixes the polarity. A coil with 1–2 % of the series field ampere-turns proved sufficient. No special complication arose from this arrangement in cases when the motor driving the welding generator was a d.c. motor, e.g. on board ship, in dockyards, or in railway maintenance service where the general supply was direct current. The only undesirable feature was the introduction of 220 or 500 volts into a low-voltage generator. But with a general a.c. supply it was necessary at first to step down the voltage, by means of a bell transformer or by tapping the motor winding, and then to convert the current, for instance by means of a dry-cell rectifier. The fact that the additional plant is designed only for very small voltage and current does not make it less complicated or much more reliable. In the case of a generator driven by a petrol or oil engine, none of these methods was available, and a separate exciter dynamo was chosen which, however, deprived the plant of the advantage that the machine was independent of the direction of rotation and required no changing of

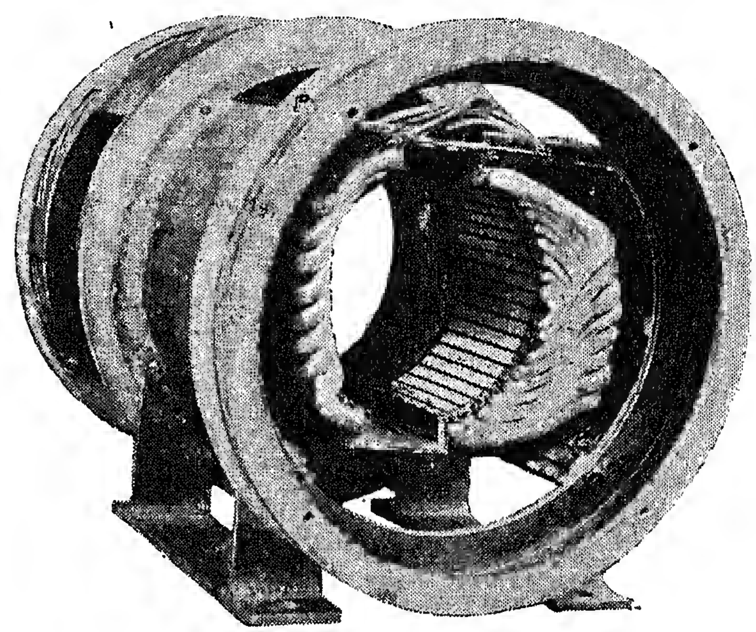


Fig. 9.—Experimental stator design with distributed winding.

wires for reversed rotation. From a manufacturing point of view, different arrangements which have to take into account the kind and direction of the drive are undesirable.

Necessity for the Fixed Pole

It may be asked whether the danger of reversal of polarity is so great that some such device is essential and vital. In fairness it should be stated that many thousands of cross-field machines are running satisfactorily without any such arrangement, and that serious complaints have come from places only where several welding operators were engaged on the same work and were negligent. Theoretically it would be difficult to say whether a machine would change its polarity without outside influence. The oscillations of magnetism set up by sudden changes in the electric circuit are not easy to calculate, especially if the magnetic circuit comprises not only laminated but also solid parts, and the electric circuit includes not only the simple series-connected parts but also semi-independent circuits formed by armature coils

that are momentarily under the same brush. One could imagine that the ordinary sudden short-circuit could produce a rush of current so much in excess of that steady value where zero voltage is reached that the field would be reversed and that this condition might have different lasting results, if the short-circuit is kept on for a full second or only the one-hundredth part of a second. But reports of reversals of polarity of a machine running by itself have only been substantiated in cases where brushes were shifted into a wrong position or where machines without regulating poles had a low-resistance diverter to the series coils, diverting a great part of the current through a path of very different self-induction. A moderate diversion of current does not greatly affect the performance of the machine. Without such by-passes for the current, which may temporarily allow the armature reaction to overpower the field, the single-running cross-field machine does not lend itself to field reversal because the rush of current does not appreciably exceed the steady full-load current under any circumstances. The observed cases of reversal were due to the accidental paralleling of two machines without an equalizing connection for the series windings. A welding operator, for instance, would in an interval of welding hang his electrode holder on to a peg which already carried a holder of another machine. Then one of the machines would send full current into the other and reverse its polarity, without the knowledge of the operators. A badly trained and inattentive operator might not even notice during his subsequent work that anything was amiss and in consequence might go on welding with wrong polarity.

If a running constant-voltage machine were connected to a stationary one on a power-house switchboard, or if two such machines with series or compound windings were switched together without an equalizing connection, the attendant would not be likely to forget the trouble following his mistake. A machine that is designed to withstand short-circuits regularly, however, shows no signs of distress when connected to a similar stationary machine or to one of different polarity or voltage. In none of these cases does the current differ appreciably from the normal working current.

Where it was possible to instruct the operators these cases did not occur. It is easy to avoid such accidental connection by seeing that each electrode holder has its own peg or is laid down on a wooden board and not on metal. Also, the re-establishment of correct polarity after reversing is a matter of seconds rather than minutes if another machine is near and if the operator is properly instructed. It may happen, however, that a shop loses experienced operators and foremen at the same time, and therefore in welding shops employing several machines on the same job machines that would not reverse their polarity were called for.

Motoring

What actually happens to the machines that are paralleled without equalizing connection? They are, as a rule, either running as two generators in series and short-circuited, with full current flowing through the two series-connected machines and no voltage showing, or one machine may be working as a generator and the other as a motor. A third case is possible. If two identical machines had identical setting of the regulating poles, both being set for the same short-circuit current and giving by chance the same open-circuit voltage, then after connection no current might flow between the machines and they might both retain their no-load voltage. But if the voltage of one machine were lower it would take current from the other, and as soon as a very small current was exceeded the field would be temporarily reversed, taking its path in the fixed pole through the magnetic shunt without reversing the permanent magnet. The current rapidly grows to the full value of short-circuit current. It does not matter whether the e.m.f. of one machine is short-circuited in the coils of one machine or whether two e.m.f.'s in series are short-circuited in the coils of two series-connected machines. Every machine shows zero voltage and full short-circuit current.

If the regulating poles of the two machines are differently set, one machine will motor and the other will generate. In Fig. 7, two curves "m" and "n," for different settings of the regulating pole, are extended beyond the point where they reach the horizontal zero line. If the current is increased beyond the value reached with the outer circuit short-circuited, the voltage becomes negative. In the same way as a positive current above the limit gives negative voltage, a negative current above that limit gives positive voltage. This happens in the case of the two machines referred to above. They both give the same positive voltage, but the current in one is reversed. The condition is quite stable. The current flowing through the combined circuit is less than the short-circuit current of one machine and greater than that of the other.

The curves drawn for negative values of current are, owing to the influence of residual magnetism and the permanent magnet, slightly different from those with positive currents. But the difference in the drooping part is barely perceptible. In Fig. 7 the current OP, for which the positive voltage PM of the upper curve is equal to the negative voltage PN of the lower curve, gives the resulting current flowing through both machines. A simple graphical way of finding the current that will flow through two machines with different settings of the regulating poles is to redraw one curve with negative instead of positive ordinates, symmetrical with regard to the horizontal axis, and to determine the point of intersection of the two curves. In Fig. 8 curve "m_0" is symmetrical with curve "m," and each of the 10 curves representing different settings of the regulating pole has a definite point of intersection with curve "m_0," showing the motoring current which the machine will take if paralleled with a machine with the regulating pole "full in."

Two machines may be run for test continuously at any point of the curve without using resistance racks. The current is reduced and the voltage increased by screwing out the regulating-pole piston of the motoring machine. The latter runs with reversed field, but after disconnecting the two machines and continuing the run the field will correctly re-establish itself, owing to the fixed pole.

MATERIAL AND MAGNETIZATION OF THE PERMANENT MAGNET

The best material for the permanent magnet is a nickel-aluminium-iron alloy, the magnetic qualities of which were discovered by Mishima in Japan several years ago and which has been made since with various modifications in several countries. Figs. 10 and 11 show the curves of British and Continental alloys of similar good performance. In the upper parts of the curves, reading from right to left, the induction in c.g.s. lines per cm^2 is shown dependent on the demagnetizing force H. The lower curves show the energy, in ergs, stored in the material, corresponding to every stage of magnetization. These hard and brittle alloys can only be cast at the present time, and grinding is the only suitable machining. The permanent-magnet tube is the only casting used in the construction of the welding machine.

When the first machines were made, many years ago, with standard cast-iron brackets, complaints were received that they did not stand up to the treatment accorded to them in mine repair work, where they were dumped down from one level to another with little care. Rather than using cast-steel brackets the author made an all-welded design for welding generators, using only mild steel and employing a construction then entirely novel, but since used also in ordinary motors and generators.* A case has been reported of a welded machine having been accidentally dropped 70 ft. without damage to any of the vital parts. Only the handwheel, the running wheels, and the axle of the running wheels, were bent, and the damage was quickly repaired. Figs. 1 and 2 show the parts of the welded welder.

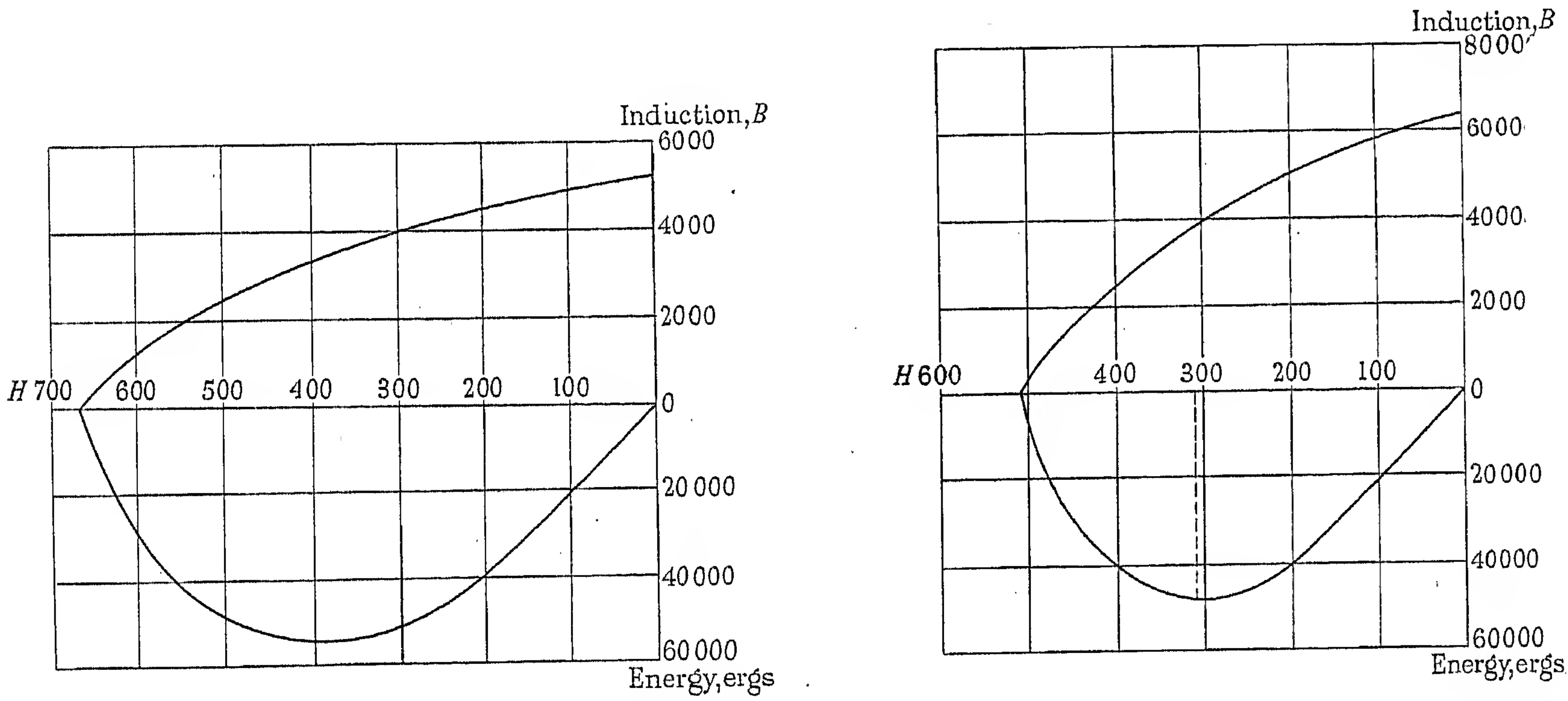
That the material of the permanent magnet is cast and brittle is no practical disadvantage, because it is securely fixed between mild-steel parts and is not exposed to any mechanical strain.

To facilitate erection and handling of the permanent magnet, it is fitted with a magnetizing coil of thin enamelled wire, EW in Fig. 1, which is used for magnetization only and not during running. The wire can carry the full-load current for a few seconds, although only a fraction of a second is required for magnetization. There is no need to magnetize the permanent magnets before assembling the machine, or to treat the magnets with the special care that would otherwise be necessary to prevent them from losing strength. After complete erection, current is passed through the coil, from either the same or another machine, for approximately 1 second.

Should the permanent magnet ever lose its magnetism, for instance if in railway maintenance service the leads of the machine should come in contact with the 500-volt supply, the magnetizing coil could be used to restore the proper polarity without dismantling the machine.

EXCITERS

The arrangement of permanent magnet with magnetic shunt can also be used in other than searchlight or welding dynamos. Exciters, for instance, with a wide range of voltage are not easily stabilized and are subjected to reversals of polarity if they are self-excited. Reversals may be caused by short-circuits in the main generator, or by quick reduction of the shunt excitation, when the current flowing through the exciter armature (connected to the highly inductive generator field) overpowers the weakened exciter field. In some cases the use of an auxiliary exciter can be avoided by employing the "fixed pole" arrangement explained in connection with the welding dynamo.



Figs. 10 and 11.—Curves of nickel-aluminium alloys for permanent magnets.

* See References (6) and (7).

REFERENCES

(Previous publications of the author, referred to in the paper.)

(1) " A New Dynamo, and its Application to Train Lighting," *Elektrotechnische Zeitschrift*, 1905, vol. 26,

p. 393; *Zeitschrift für Elektrotechnik*, 1905, vol. 23, p. 273; *Electrician*, 1905, vol. 55, p. 297.
(2) "Progress in the Design of D.C. Machines for Constant Current," *Elektrotechnische Zeitschrift*, 1906, vol. 27, pp. 1035 and 1061; *Electrical World*, 1906, vol. 48, p. 918.
(3) "D.C. Dynamo for Arc Welding," *Elektrotechnische Zeitschrift*, 1928, vol. 49, p. 43; *Elektrotechnik und Maschinenbau*, 1928, vol. 46, p. 61.
(4) "The Direct-Current Cross-Field Machine" (Julius Springer, Berlin, 1928).
(5) "Progress in the Design of Regulating-Pole Cross-Field Machines," *Elektrotechnische Zeitschrift*, 1929, vol. 50, p. 1188.
(6) "Welded Welding Generators," *Elektrowärme*, 1933, vol. 3, p. 372.
(7) "Automatic Carbon Arc Welding," *Welding Symposium*, 1935, vol. 2, p. 158.

DISCUSSION ON "THE USE OF PROTECTIVE MULTIPLE EARTHING AND EARTH-LEAKAGE CIRCUIT-BREAKERS IN RURAL AREAS"*

SCOTTISH CENTRE, AT GLASGOW, 10TH JANUARY, 1939

Mr. W. Sutcliffe: The best method of earthing an installation is a subject which has always exercised the minds of engineers responsible for safety in the public supply of electricity, and many will recall Mr. W. W. Lackie's paper† on the subject. It was recommended therein that all steel conduit or lead coverings should be carried on insulated supports, and earthed through a resistance and relay at one point only, the former to limit the fault current and the latter to actuate a local bell circuit to give an audible and continuous warning in the event of an earth fault. Installations in certain public buildings were so arranged, but ideas have since undergone a change, and solid earthing to water pipes, with the clearing of faults through fuses, has become standard practice.

Direct earthing is simple enough in towns and villages having public water supply mains, but, as the author says, difficulties arise in rural areas where electrodes must be employed; that these are unreliable is clear from Fig. 1, which shows a variation from 0·35 ohm to 3 000 ohms in the measured resistances of earth connections at consumers' premises. Rod and plate electrodes seem particularly bad, in view of the statement on page 764 (vol. 81) that "of the installations using a plate or rod electrode, none would blow a 10-amp. fuse in 1 minute."

The author seems lukewarm in his attitude to earth-leakage circuit-breakers and, whilst he suggests that they provide a solution to the problem of protecting consumers against shock in rural areas, the list of disadvantages on page 765 (vol. 81) leads one to the conclusion that he regards their use as an expedient to be avoided if possible; this is not surprising, following the disappointing results of 37 switches examined and tested [referred to on page 772 (vol. 81)], 70 % of which failed to trip at or below 30 volts, i.e. the potential agreed by the E.R.A. as the maximum permissible.

Protective multiple earthing of the neutrals, whilst not receiving unqualified approval, appears to be the author's choice, but here again, as suggested in the paper, risk is still present under certain conditions, e.g. a line-to-neutral fault or a break in the neutral distributor. One is therefore led to the conclusion that immunity from risk of an electric shock from a faulty electrical apparatus installed in rural areas, without good earthing facilities, cannot be guaranteed by any of the methods or devices described in the paper. Would the author recommend a supplementary earth conductor of adequate section, from substation to consumers' premises, connected to an earthed neutral at the transformer, and linked up in multiple manner with the neutral and earth electrodes at the consumers' end of the line? Surely such an arrangement, whilst costing the supply authority a little more, would represent a praiseworthy attempt to respect the excellent precept expressed in the opening sentence of the introduction to the paper.

Mr. H. A. McGuffie: I have been connected with a considerable number of experiments made with various types of earth tripping gear, and I know that this type of gear has a hasty habit of tripping when it is not supposed to do so. It is undoubtedly a delicate piece of apparatus to install in a consumer's premises where the maximum load is, say, about 5 amperes. Both in Scotland and in England I have had complaints where we have installed gear of this type.

I am coming to the conclusion that if we were to spend a little more money on soundly earthing consumers' premises or insisting on these being soundly earthed in both rural and town areas, we should be much better off. At the same time I am not definitely saying that in all rural districts installations can be or are earthed properly. On a large installation when earth-leakage-trip gear is being installed, especially when it has to be subdivided as in the case of a large rural consumer who has several different types of appliances, it becomes a somewhat complicated business unless a large number of switches are employed, which lead to other troubles.

At present we cannot enforce earthing beyond a certain point, but I think something should be done on these

* Paper by Mr. H. G. TAYLOR (see vol. 81, p. 761).
† *Journal I.E.E.*, 1905, vol. 35, p. 116.

lines, in which event we shall experience less trouble from shocks at cookers, etc.

Mr. A. P. Robertson: Dealing with Fig. 11 in connection with multiple earthing, the author said that when a fault occurred in any premises the voltage might rise considerably, and in some cases it was shown to be about 200 volts. With all these adjacent earths would the apparatus in adjacent consumers' premises rise to the same voltage, being earthed through a neutral, or connected through a neutral with the faulty apparatus? It would be rather unfortunate if some consumer who would not spend money on good apparatus were to endanger everybody adjacent to him. That may not be the case, but it is possible. With all these multiple earths it would be impossible, or at any rate very difficult, to test for faults on the neutral without disconnecting them all.

At the beginning of the paper the author refers to blowing fuses of 5 and 10 amperes. That would take a very considerable earth fault. Later he talks in terms of milliamperes. Is it the case that in some instances protection is obtained by fuses and in other instances by very delicately set circuit-breakers? Unless circuit-breakers are operated occasionally, they are inclined to stick when called upon to clear a fault. A very delicate circuit-breaker operating on a few milliamperes would possibly add considerably to upkeep costs, so that a lot of testing would be required on this type of apparatus. Who is to test them, the undertaker or the consumer? I recognize, of course, that the paper refers mostly to rural undertakings. Where there is a multiplicity of water pipes it is possible to get a good earth, and in that case I assume that the author agrees that only one point should be earthed.

Mr. W. J. Cooper: I am inclined to agree with Mr. Sutcliffe that the provision of an earth might reasonably be considered to be part of the responsibility of the undertaker. Can the author say what the relative economics of the two methods of protection are, and whether it would not pay the authorities to provide an adequate earth to the whole distribution system, including the consumers' premises?

Mr. H. G. Taylor (*in reply*): No perfect system of protection has yet been devised, though it is not difficult to improve on the existing conditions in rural areas. A supplementary earth conductor on the lines described by Mr. Sutcliffe has been used in a number of cases and is quite effectual, but special precautions should be taken to guard against a live wire making contact with the earth wire.

I agree with Mr. McGuffie that undertakings could in many instances advantageously spend more money on earthing. I am convinced that the old-established practice of earthing could frequently be made to give satisfaction, but there needs to be a radical change of outlook not only with respect to the technique but also with respect to the cost of earthing.

Fig. 11, referred to by Mr. Robertson, relates to the voltage-rise of the metal framework which takes place when a fracture of the neutral distributor occurs. A fault on any one consumer's premises does not endanger adjacent consumers. It is admittedly impossible to find neutral earth-faults, but, since the neutral is deliberately earthed at many places, the necessity for finding them is not apparent. Protective multiple earthing involves the blowing of fuses, and in this respect is no different from a normally earthed system using the water mains or the service cable sheath as the earth electrode; earth-leakage circuit-breakers, on the other hand, require operating currents of between 15 and 60 milliamp., depending on the design. With regard to the testing of such switches, no general rule exists, though it is thought that in the majority of cases so far it has been left to the consumer. In Sydney, where the use of earth-leakage circuit-breakers is compulsory in all new installations, the test is made by the meter reader. There is no advantage in changing from the one-point-earth system now used where a low-resistance water-main network exists, though there is some evidence that non-metallic pipes may before long become so common as to make it desirable always to check the resistance before assuming, as heretofore, that water mains automatically provide a low-resistance earth connection.

A supplementary report to be issued by the E.R.A. will provide an answer to Mr. Cooper's point about cost, though it has been found impossible to do more than set out all the items which must be considered in making a cost comparison.

DISCUSSION ON

"THE TREND OF DESIGN OF ELECTRIC LOCOMOTIVES"*

EAST MIDLAND SUB-CENTRE, AT DERBY, 15TH NOVEMBER, 1938

Mr. F. Nicholls: I should be glad if the author could express his opinion as to why there are only 670 miles of electric traction in this country. Does this figure include underground services?

I note that in other countries the single-phase motor is preferred to the d.c. third-rail method employed in this country. I remember that when some years ago on the Southern Railway (London, Brighton and South Coast section) the portion from Victoria to Croydon was electrified, the single-phase system was adopted. Subsequently, upon amalgamation, that system was scrapped and replaced by the d.c. third-rail system which exists at the present time. Perhaps the author could say why the single-phase system was scrapped. Was it done in the interests of standardization?

The author mentions the reluctance to change rapidly from steam to electric working; probably one reason for this is the exceptionally high efficiency which the British steam locomotive has attained.

I should like to refer to the train that is running in Germany, known as the "Hamburg Flyer." It is a light train (about 150 tons) which attains a very high speed, and is Diesel-electric-driven. It seems to afford a very good example of the trend of modern design, and I should be glad if the author would express an opinion on the possibility of adopting that form of traction in this country.

Mr. S. J. R. Allwood: When ordinary series control is employed, rheostatic losses are obviously high. Has Metadyne control yet been developed sufficiently for use with locomotives? An extraordinary locomotive with Metadyne control has been built for the L.P.T.B., but it is of a comparatively small type.

I am wondering whether the standard voltages which we have attempted to adopt in this country, namely 1 500 volts (d.c.) or 3 000 volts (d.c.) for main-line tracks, are the most suitable, seeing that they have led to the abandonment of the a.c. motor, which is now comparable in performance with the d.c. motor. The saving due to tap-changing is of course obvious, and one can push the line voltage up to whatever value one wishes. Cutting out rheostatic losses, and taking a broad view, however, it seems to me that there is a great possibility that this country has made a bad choice.

With reference to the use of rectifiers on locomotives, I believe that an attempt to adopt a high-voltage single-phase system for traction purposes was one of the causes which led to the development of the large steel-tank rectifier. A locomotive was built in America nearly 20 years ago embodying a steel-tank rectifier. Details of the development in this direction since then would be of interest.

The majority of the locomotives referred to in the paper appear to be rather larger than would be required for electric traction in this country. The reasons for this are that our distances are shorter and trains lighter, and because of our supplies of cheap coal a change-over to electric traction in this country is more likely in suburban areas than on main lines. It appears to me that electric locomotives for traction are developing less rapidly in this country than in other countries where coal is dear.

Mr. E. M. Frost: All the locomotives shown in the author's slides are reversible without difficulty, and may be controlled from either end; this may be quite convenient for short routes, but on long-distance express trains would it not be better to have the control cabin at one end only, in the interests of streamlining and equipment layout?

As to Diesel-electric versus electric locomotives, the Diesel-electric locomotive is equivalent to the steam engine in that it carries its own fuel and creates its own tractive effort. I think the advantage of electric traction is that with it one can increase the horse-power, whereas in a steam locomotive the output is limited. In spite of the increased efficiency of large-scale electrical generation and equipment, the use of electric locomotives seems limited to steep gradients. In Italy, where they have ample water power and steep gradients, the development of electric traction has been very great, probably because for economic reasons they have to use and build only electric locomotives.

From the author's slides it would appear that there is a large amount of window space on electric locomotives. Are all these windows necessary?

To what is the noise made by these locomotives generally due?

Mr. E. W. Porter: The author would not, I assume, recommend the use of nose-suspension of the motors on locomotives designed for speeds higher than about 60 m.p.h., although it may be used successfully on coaches at higher speeds than this.

Generally speaking, the Continental and American designs of leading bogies appear to be much more complicated than their English counterparts, and they endeavour to control the side movement to a much greater extent.

The fact that many old steam locomotives ride well at high speeds is probably accidental, arising from their naturally high centre of gravity and their weight distribution. The electric locomotive does not lend itself so readily to the same treatment.

When the Buchli drive was first introduced I thought that it was extremely promising, and it is interesting to find that it has remained in favour for such a long period.

* Paper by Mr. C. E. Fairburn (see vol. 83, p. 581).

Regarding the quill drive, which the author favours, is not the bearing speed on the quill liable to be excessive in the case of a high-speed locomotive?

Streamlining is a modern fashion, and, like most fashions, is liable to be expensive; it should only be employed on locomotives to clean up the general appearance, and should not be carried to the extreme limits which are so much in favour in some quarters.

Mr. E. A. Langridge: In the paper it is stated that rod drives have to be kept within very fine limits. In the case of the G.I.P. locomotive the axle-box rises and falls in the guides a considerable amount, and I should like to know the limits required under such circumstances.

I had always imagined that electric locomotives rode very comfortably on the track, and it is therefore interesting to observe from Fig. 14 that the designer of the electric locomotives referred to had to go to some trouble to get his oscillations down to the level of those given by a 2-cylinder K4S steam locomotive. Probably a 4-cylinder steam locomotive would show better riding qualities than the electric locomotives referred to in Fig. 14. I think this is greatly to the steam-locomotive designer's credit.

Many locomotive engineers in this country have strong opinions regarding the use of the 2-wheel truck, and therefore, referring to the lists of engines at the end of the paper, it is surprising that so many express locomotives have a 2-wheel truck, leading or trailing. Has any trouble been experienced due to these trucks becoming derailed?

With reference to the Westinghouse spring drive shown in Fig. 12 (Plate 3), the amount of space between the spokes is rather remarkable. The tendency in steam-locomotive design is to space the spokes much closer and so keep down the high stress in the tyres at these points. This is illustrated in papers by Prof. Coker, who used polarized light to examine such specimens. Has any trouble been experienced with these tyres?

Mr. A. H. Edleston: I should like to know something about the flexibility of the machines described in the paper. Can the author give any idea as to what overload the motors in the latest-type electric locomotives can be run at, and for how long? Could they, say, be overloaded up to 75 % for any considerable period?

In one of the locomotives described by the author laminated springs were used at first, and later a combination of laminated springs and coil springs was substituted. Was this arrangement adopted on account of laminated-spring failures with nose-suspended motors?

Mr. A. E. Owen: Switzerland has large water-power resources; if she had coal to the same extent as we have in England, I have no doubt she also would employ the steam locomotive.

What is the mileage and the time-interval between general repairs on electric locomotives? About eight years ago the Institution of Locomotive Engineers visited Switzerland, and at Belinzona we were shown a locomotive being stripped for heavy repair; they said it had done over 100 000 miles, and that it would take 6 months to overhaul. Steam locomotives are doing about 120 000–150 000 miles between overhauls, and can be repaired in about 2–3 weeks.

Mr. H. Forbes: I should like to point out that Diesel traction gives all the advantages of electric traction at a fraction of the cost. Every argument for electrification is just one more argument for Diesel traction. I have myself known examples where suburban areas have been worked by Diesel-engined locomotives, and the running cost has been 6d. per mile as compared with 11d. for steam tank engines.

In Rumania, on the Brasov line, one Diesel locomotive replaces six steam locomotives, altogether doing the work of three low-speed locomotives which were used to haul the trains up steep grades. Electrification was not possible in this case.

Has electromagnetic braking been adopted for electric locomotives, and has it any effect on rails, due to magnetic action? I have heard that the rails become marked with blue burns after prolonged application of electromagnetic brakes.

[The author's reply to this discussion will be found on page 436.]

MERSEY AND NORTH WALES (LIVERPOOL) CENTRE, AT LIVERPOOL, 9TH JANUARY, 1939

Prof. F. J. Teago: The paper would have been more valuable if pictures of the locomotives mentioned had been included, and I suggest that The Institution might undertake to publish a small book containing drawings of the world's most notable electric locomotives, present and past.

I agree with the author that in general the desire for "more power" will finally secure the electrification of railways. So far as England is concerned, however, I doubt whether this is true, because our immediate problem is one of "more mobility" rather than "more power" or "more speed." It might be more profitable for us to think in terms of the motor-coach rather than the locomotive, where the desire is to produce extreme mobility.

Referring to Figs. 1, 2, 3, and 4, I think it should be made quite clear that the term "double-bogie" refers to the motor bogies. The author says that possibly readers of the paper will have drawn conclusions different from his own in regard to the locomotives referred to in these Figures. I would mention here that the Pennsylvania GG1 locomotive, which to my mind represents the most up-to-date design and performance, is a double-bogie one. The Pacific type of steam locomotive is well known for its steady running at high speeds, and it is interesting to note that the Pennsylvania locomotive is virtually a double Pacific with no trailing bogie. In fact, the Pennsylvania locomotive (Fig. 14) is shown as having better riding qualities than the K4S type. This is a Pacific-type steam locomotive, practically the same as our own only that it is heavier; the K4S weighs 140 tons, against the Pacific's 100 tons. These facts make me

favour the double-bogie electric locomotive, which also has excellent riding qualities. Against the double-bogie electric locomotive the author quotes tests made in Sweden, from the results of which the Swedes concluded that double-bogie locomotives were not so good at "start" as single-bogie locomotives; can the author tell us whether these double-bogie locomotives were equalized? Without equalization, their poor starting performance would be understandable, owing to the redistribution of weight which takes place at starting.

When he refers to "nose suspension" I presume the author means the type where some of the weight of the motor is carried on the road-wheel axle without the interposition of springs.

I consider that the Westinghouse type of drive, introduced in 1914–18, is the most flexible one ever devised; it was abandoned for a time because of the large number of breakages of springs which occurred with it. It has since been discovered that one reason for the spring breakages was "decarburization" during heat treatment; this type of drive is, however, again to the fore as the result, among other things, of improved heat-treatment technique. The advantage of the Sécheron form of drive is that when the road wheels are displaced ample restoring forces are called into play. None of the other drives have that property to the same extent: in fact, one objection to the Buchli drive is its excessive freedom. The modified Westinghouse drive (Fig. 11) is employed for the GG1 locomotive, and this form of drive can carry large weights—the Pennsylvania locomotive has about 22½ tons per driving axle. I rather fancy, however, that the rubbing plates are a source of weakness in this Kleinow modification, and it lacks complete restoring forces.

I see on looking through the tabulated information that 77 % of d.c. locomotives have nose-suspended drive, 12 % quill, 7 % gear, and 4 % jackshaft; and that 5 % of a.c. locomotives are nose-suspended, 45 % quill, 19 % gear, and 31 % jackshaft. I should like to ask why d.c. locomotive motors are practically all nose-suspended, and why nose-suspension is so unpopular with the builders of a.c. locomotives.

Mr. R. Varley: I should like to ask the author whether it is generally found in practice that the riding at high speeds of locomotives with frame-mounted motors is steadier than that of locomotives with nose-suspended motors. The riding of the multiple-unit stock forming the express trains in the South of England is very rough at speed, and it would be interesting to have the author's opinion as to whether trains hauled by electric locomotives would give better results.

I am pleased to note the tendency to clean up the outside of electric locomotives, and thus improve the appearance of what has hitherto been a very ugly-looking object, in addition, of course, to reducing power consumption at speed.

I was very interested in the remarks on roller bearings. There is no doubt, however, that they have proved very satisfactory on multiple-unit stock.

With reference to the spherical type of bogie centre, I should like to know what method of lubrication is adopted. I have had experience with this type of bogie centre on trailer coaches and have found it very necessary to provide adequate lubrication to ensure free working.

Can the author say whether the Metadyne system has been tried out for locomotive work? It would appear that this system could be adapted quite satisfactorily and would give very smooth operation.

Mr. R. Brooks: The author's reference on page 583 to the G.I.P. freight locomotives may be amplified by mentioning one further consideration. The choice of side-rod construction was also influenced by the need for a design which could operate in flood water 4 ft. deep. The axle exciters are so designed that they can be made watertight in order to meet this condition. It is on record that these locomotives proved very valuable for general service in flood conditions when other types of tractor were unusable.

While it is true, as indicated on page 590, that during the period under review there have been no spectacular developments in the control equipment for motor-coaches and locomotives, substantial detail design progress has been made, resulting in equipment on which the maintenance cost is very low indeed.

Turning to the subject of current collection from overhead lines, the tendency to change to single-pan construction has one further aspect that has not been mentioned. At speeds of over 35 m.p.h. difficulty is experienced in maintaining equal pressures on the two pans of a double-pan pantograph, and at higher speeds practically all the pressure is concentrated on the leading pan, with consequent increased wear. The single-pan type is unaffected by speed, and experience tends to the belief that a well-designed single pan is superior even for very heavy currents.

The author summarizes on page 593 several advantages of electric braking; probably the most important of these is that by its use higher operating speeds are possible down gradients, as the mechanical brakes on locomotive and train are kept cold and therefore in a fit condition to stop the train when called upon in an emergency.

Mr. A. Tustin: Railway electrification has been held back in the last decade—the period covered by the paper —firstly by the economic breakdown of 1929, and since that date by the unprecedented diversion of the world's investable resources to war purposes. If international order is restored, the world's governments will find themselves forced to plan for the useful absorption of the labour and resources freed from armament work, and railway electrification on a large scale will be one of those sources of profitable re-employment which many governments are likely to put in the forefront of their plans. It is clear from the paper that the wide and varied experience that has been gained, and is being gained, by the electrical industry, will enable it to meet all the technical requirements of the future, and to supply economical and relatively trouble-free equipments.

I should like in this connection to comment on the paragraph in the section of the paper headed "Motor Design" that deals with the progress in design of the direct-current motor. The author seems to imply that the designers have been less successful in increasing the power/weight ratio in the case of railway motors than in the case of tram and trolley-bus motors, and I think that his remarks may easily give a false impression. In the first place, it is obvious that the firms that design and produce the modern lightweight trolley-bus motor—

which is certainly a wonderful machine—are not likely to fail to apply similar principles and improvements and the same pressure towards improvement in the even more important field of railway work. The real facts are that to some extent the design of smaller machines has been brought up to the high standard already existing in railway motor work. Ventilation has been improved, modern Class B insulation has been made universal, and the designs have been perfected by long periods of experiment. There has also been noteworthy progress in the design of d.c. traction motors. Freedom from commutation troubles and flashing-over has been made a matter of more precise knowledge by prolonged theoretical and experimental work. High interpole-armature ratios are used, with divided interpole gaps, and great care is given to the design of the magnetic circuit of the interpoles. The behaviour of the motor under all transient conditions may be predetermined. Steps have been taken to reduce losses and so reduce the weight by the increasing use of tapered slots, laminated or subdivided armature conductors, and specially controlled field forms. The degree of ventilation employed has shown a tendency to rise, and the distribution of the ventilating passages has been greatly improved. In the field of insulation the last few years have seen the introduction of the various glyptal varnishes, moisture-resisting and anti-tracking treatments, and great improvements in asbestos products. The design of motors capable of running at peak temperatures of 200° C. is now practicable. The use of these high temperatures is economical, particularly in cases where occasional heavy grades occur, on which the motor is overloaded, so that while the motor size is not increased to cater for these conditions the efficiency is high for the more normal conditions of operation.

I should be interested to learn the author's views on the desirable degree of forced ventilation of railway motors. There is no doubt that a further increase in the amount of ventilation, though necessitating an increase in the size of the blower motors, would decrease the total weight of the equipment. The power consumption would, however, be slightly increased.

Voltages of 1 500 and 3 000 volts (d.c.) have now become standardized for electrical locomotives. There is no reason from the point of view of electrical machine design why still higher values, such as 4 500 or even 6 000 volts (d.c.), should not be used, with the object of economy in transmission, if circumstances require such a solution. It would be interesting to have the author's views on the limit of maximum economical d.c. voltage in special cases.

Mr. G. W. Parkin: One cannot but notice that the transmission of power from the motor to the wheel tread has in many instances only been achieved by incorporating in the drive a complexity of precision-machined components, particularly with respect to collective drives, where it is essential that main frames should be substantial and working clearances of a fine order so as to maintain coupled axles in perfect alignment. Although for a given adhesive weight collective drives may prove to be slightly superior in service, I do not imagine that load variations on axles of individual-drive equipments due to torque reactions and permanent-way slacks will be appreciable. Have curves been plotted of, say, maximum drawbar pull per ton of adhesive weight against speed, for collective-drive and individual-drive locomotives of similar characteristics?

Referring to the two simplest forms of individual drive —gearless and nose-suspended—although the weak features of these drives are generally well known it is of interest to note that nose suspension is used on the majority of d.c. locomotives and also on the 2–C–C–2 5 000-h.p. experimental turbo-electric locomotive for the Union Pacific Railroad, credited with a maximum operating speed of 125 m.p.h. at a working weight of $236\frac{1}{2}$ tons and with relatively small driving wheels of 3 ft. 8 in. If, therefore, it is accepted that a reasonable degree of satisfaction is afforded by this type of drive, does it not follow that there is a field for the simplest drive of all (the gearless)? Since in this type the field structure is carried on the bogie frame and with the armature spring supported on the axle, dead weight on the axle will be reduced to a minimum while the centre of gravity of the whole unit (admittedly unavoidably lower than might be desired) will not be appreciably lower than that obtaining with a typical nose-suspension design.

Dr. H. L. Haslegrave: On page 583 the author says that the present tendency is towards the use of larger single units, and that general experience with high-power locomotives shows that even larger horse-powers are desirable, and would be economically sound on many lines carrying heavy traffic. This would seem to nullify some of the advantage of electric traction. There may be a saving in cost of the units, but not all trains require big units, and I should have thought that the grouping-together of two or more single units when large powers were necessary would lead to a more efficient use of the driving stock. This would, I imagine, apply particularly in England, where the density of traffic prevents the use of very long trains. I should like to ask the author in what way the higher powers will be obtained. With high speeds there is more wear on wheels and rails, and consequently the weights on each axle should be reduced. It would seem to me that the tendency to obtain higher power would mean using more driving axles, and paying more attention to the drive.

In referring to the individual-axle drive the author says that the type of drive with the armature mounted on the axle is not being adopted now because of the large value of the unsprung weight. Were there not other reasons for its being abandoned, such as the difficulty experienced in lubrication? One disadvantage of this type of drive is the large value of moment of inertia in a plane at right angles to the direction of motion, which results in the gyroscopic action giving rise to considerable vibration. I should think it likely that the Buchli drive produces vibration in this way, owing to the inertia effect of the large gearwheels. Steam locomotives seem to have an advantage in this respect, which is not neutralized completely by the disadvantage of the use of cranks and connecting rods, and this may account for the fact that less wear on the rails and tyres is sometimes experienced with steam locomotives as compared with electric locomotives of the same power and speed.

The author says that he is surprised to find that roller

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bearings have not been adopted to a very great extent. Roller bearings receive a large amount of shock in starting and in running, and it seems to me that they are less able to withstand this shock than plain bearings. Since no provision is made for forming the oil film during starting, plain bearings start under boundary lubrication conditions with higher friction than is experienced with roller bearings, but after a certain speed an oil film is formed and the friction is reduced considerably. This probably accounts for the advantage in running conditions experienced with plain bearings at certain speeds. In practice the best design for film conditions cannot be adopted with bearings used in locomotives, because of the heavy starting conditions when no film exists. I should like to ask the author whether pressure oil feed is being used for all the bearings on locomotives.

On page 588 it is stated that streamlining has no great advantage, and one of the author's slides showed a locomotive where streamlining was brought down almost to rail level, the wheels being shrouded. I do not think that streamlining can have any affect up to 60 m.p.h., and it cannot have any great effect unless it is carried down to the track. It is rather interesting to note that on the "Coronation Scot" shrouding of the wheels is not adopted.

On page 590 the author says that not much progress has been made in the design of d.c. motors. It seems to me that a.c. motors offer more scope for improvement than d.c., in that more types can be used; but advances have been made in d.c. motors. In particular, balancing and commutation have been improved during the period covered by the author's review. In the period about 1926–28, I believe that the Swiss Federal Railways used two methods of speed variation—brush-shifting and induction regulators—which are not mentioned by the author. Have these methods since been completely abandoned?

It seems to me that future advances in the design of locomotives in England will depend upon the policy adopted. On impartial review steam locomotives do not seem to possess any great disadvantages as compared with electric locomotives. No mention is made in the paper of efficiency, but I rather suspect that, if one could measure efficiency, one would find that the steam locomotives were better in this respect than electric locomotives. Perhaps two of the main advantages of electric locomotives are high acceleration and cleanliness, which are more important for short-distance stopping trains than for long-distance fast trains. It would therefore seem feasible that future policy in England might lie in the adoption of electric traction for short-distance trains and for long-distance stopping trains, and of steam traction for long-distance fast trains. This would necessitate steam trains running on the same lines as electric trains, but experience of this has been gained in Switzerland.

I should like to ask whether the author has any knowledge of the behaviour of the large battery locomotive built for the London Passenger Transport Board early in 1938. Apart from use for train-forming purposes, it might be applied to local lines in which Diesel locomotives are now used, and to local lines on which traffic has been discontinued.

Mr. O. I. Butler: With regard to spring drives, the author mentions that recently a modification has been introduced in motor-coaches in which the springs are mounted on the gearwheel instead of on the driving wheel. I assume that the motor frame is then suspended on the road-wheel axle in the usual way, with the net result that the unsprung weight of the motor frame still exists, whilst the portion of unsprung weight due to the armature has been eliminated. I should be glad if the author would confirm this view.

A previous speaker, Mr. Varley, has referred to the possibility of applying the Metadyne system of control to locomotives. I should imagine that the continuous loss of power which occurs in operation would limit the application of the Metadyne to suburban motor-coach work, where the resistance-control method is very inefficient and where the regenerative simplicity of the Metadyne can be fully utilized.

The field coil referred to on page 590 is very interesting, and appears to represent quite a bold step in design. The omission of the usual spring clamping washers avoids an arrangement which served to maintain the field coil rigidly in position under all possible conditions of three-dimensional expansion and contraction of the coil. It is perhaps too early yet to judge the success of the new construction.

It is illuminating, but not unexpected perhaps, to read the author's comments with regard to the fact that few new designs incorporating side-rod drive have appeared for some years. The fact that the driving system in a steam locomotive terminates in the steam cylinder, where the elasticity or cushioning effect of the compressed steam compensates for inaccuracies in the construction of the drive, allows satisfactory operation of the locomotive without undue maintenance. The absence of such a cushioning effect in the case of an electric locomotive has shown the mechanical weakness of the unwieldy side-rod drive, and must inevitably result in its disappearance except for cases where the question of maximum and continuous adhesion between track and road wheels is sufficiently serious to warrant the extra maintenance of the side-rod drive.

THE AUTHOR'S REPLY TO THE DISCUSSIONS AT DERBY AND LIVERPOOL

Mr. C. E. Fairburn (*in reply*): In replying to these discussions it is interesting to observe the amount of attention which speakers at all the meetings where the paper has been read have paid to mechanical design. It appears that, in comparison, present-day designs of electric equipment are more readily accepted.

I am replying to these two discussions jointly, and I propose to deal with the various matters raised in the same order as they appeared in the paper. Certain of the points raised have already been dealt with in my reply to the discussions at London and Glasgow (see vol. 83, p. 630).

Referring firstly to the scope of the paper and to Prof. Teago's disappointment that the Tables were not illustrated by drawings of the locomotives included, I regret that I was unable to undertake the relatively large

amount of work involved. I think his suggestion that such drawings should be published by The Institution, and the suggestions of speakers at other meetings that The Institution should maintain current tables of electric locomotive characteristics, deserve serious support.

In reply to Dr. Haslegrave, the observations I made about the increasing size of locomotives must not be taken as applying universally, since there will obviously be instances where multiple locomotive operation is more economical—as for example, to take a case already quoted, in South Africa. In general it is cheaper to increase the power of electric locomotives by increasing the number of driving axles rather than to increase the maximum axle load and to strengthen the track correspondingly. One of the advantages of electric locomotives is the ease with which higher powers can be obtained without imposing increased stress on the track.

The relative merits of rod and individual drives have already been treated at some length. There are very little data available on a strictly comparable basis to show the limiting adhesion of the two drives, and I am unable to give curves as one speaker requests. In answer to Prof. Teago, the double-bogie locomotives mentioned in connection with the tests in Sweden were, I believe, non-articulated and non-equalized. Prof. Teago is correct in believing that the " nose-suspended motor " is one where some of the weight of the motor is carried directly on the road-wheel axle. On all locomotives or vehicles, except those intended for low speeds only, the question of whether the nose-suspended motor or the frame-mounted motor shall be used is primarily one of cost, taking into account first cost, maintenance costs, and, so far as these can be ascertained, track maintenance costs. From the point of view of easy riding at high speed, the frame-mounted motor is certainly to be preferred, but I cannot agree with Mr. Porter that 60 m.p.h. must be considered the limit for the nose-suspended motor. I do not think it has been clearly established where this limit lies, but it will obviously vary in each case with the weight of the motor concerned and the construction of the track. The reason why the nose-suspended motor is used so much more on d.c. locomotives than on a.c. locomotives is probably connected with the way in which each type of motor has developed. The a.c. motor was originally built only in large sizes, and it is only relatively recently that small units suitable for nose suspension have been produced. The d.c. motor, on the other hand, was originally supplied in small sizes for tramcars, for which purpose the nose-suspended type was evolved.

As far as weight on the axle is concerned, the gearless motor can show no advantage over the nose-suspended motor, and as the total motor weight to be carried by the locomotive is considerably greater than with geared motors there appears to be no reason for the use of the gearless motor at the present time. As Dr. Haslegrave mentions, it has several serious limitations in electrical and mechanical design.

Regarding the wear on Kleinow cups, I understand that this is not unduly high and that the wearing pads can be replaced cheaply by welding. There has recently been described a modification, the " Sécheron Meyfarth " drive, in which the sliding surfaces are replaced by short ball-headed links which are accommodated inside the cups and which take up the relative movements by oscillation.

In reply to Mr. Varley, it is, of course, easier to provide comfortable passenger accommodation at high speeds with locomotive-hauled trains than with multiple-unit stock. In cases where multiple-unit stock is used the choice is generally dictated by considerations such as the layout of terminal stations where the train movements required make it impracticable to use locomotives.

In reply to Mr. Butler, the spring drives used on motor-coaches to which I referred are exactly similar to the equivalent types described in the paper, except that the springs are mounted on gear wheels or discs on the quill and the spiders transmitting the torque are mounted on the rod wheels; the whole motor weight is therefore spring-borne.

In reply to Mr. Langridge, the choice between two axle trucks and a single pony axle is to some extent a question of historical development on the railways concerned, although in some designs a single pony axle could not carry the weight borne by the two axle trucks used. There appears to be little evidence that the 2-wheel truck is more liable to derailment and, in fact, most express steam locomotives have a 2-axle truck leading. In the paper the term " double-bogie locomotive " was used to describe locomotives with two bogies all the axles of which are motored. When these two bogies are coupled together and the drawgear is attached to their outer ends they are described as " articulated double-bogie locomotives." When a locomotive has carrying axles and the driving wheels are mounted in two frames coupled together it is described as an " articulated locomotive," irrespective of whether the body is split or not.

Several speakers have raised points in connection with lubrication, but the methods in use on electric locomotives do not depart to any large extent from those on steam locomotives. Bogie centres are arranged for a periodical replenishment of oil or grease, as in carriage stock. I know of no case where a pressure feed to the axle journals has been adopted, but certain types of flexible drives have been fitted with an oil pump and a re-circulated lubricating system. Although the rubbing speeds of quill bearings are higher than those of the driving axles, the loads are lighter and no difficulties are experienced with ordinary methods of lubrication; in any case, the rubbing speeds are low compared with those of stationary electric plant.

There have been instances, especially in America, where axle loads and tractive efforts per axle are high and trouble with loose tyres has been experienced, but I have not heard this attributed to the small number of spokes used with some spring drives.

As regards motor design, I dealt with the question of the development of the d.c. motor in a previous reply. The overloads which can be sustained without damage depend very much on local circumstances, i.e. ambient temperature and initial temperature of motor. It is difficult to give figures, but most designs could sustain a current of 150 % or 175 % of the 1-hour rated current for a short time. The degree of forced ventilation to be adopted cannot be stated for the general case. It is largely dependent on the internal design of the motor.

Considerable interest has been shown in the Metadyne

control system for locomotives, but in this connection I have nothing further to add to my reply to the previous discussions. I was interested in Mr. Allwood's remarks concerning rectifiers on locomotives; so far as I know, the only development which has been tried extensively under normal operating conditions is that in Germany which is referred to in the paper. Control systems on a.c. locomotives incorporating induction regulators have never been widely used, probably on account of the weight of the regulators. Motors controlled by brush-shifting have never passed the development stage for locomotive work, and I do not think any developments with such motors may be expected in the near future.

The relative merits of the single-pan and the double-pan pantograph, particularly on d.c. systems, are still an open question. It is difficult to assess the results obtained with different designs, owing to variations in the construction of the contact systems with which they are used.

In reply to Mr. Owen, certain maintenance figures for electric locomotives were given by speakers in the previous discussions. The case Mr. Owen met in Switzerland illustrates the progress which has since been made there, and which is mentioned in the paper (page 589). Under comparable conditions the time required for the heavy overhaul of an electric locomotive is no greater than that required for a steam locomotive, and such overhauls are required at considerably longer intervals; the intervals between inspections and minor overhauls are also considerably longer.

A number of speakers have raised points outside the scope of the paper which I will mention briefly in conclusion. The mileages of electrified lines in various countries shown on the first lantern slide were those actually converted from steam operation and did not include city railways constructed initially for electric operation. The figure for Great Britain did not include the lines of the London Passenger Transport Board. Since these statistics were compiled there have been further extensions, and when schemes now in hand are completed there will be 1 000 miles of electrified line in Great Britain.

As improvements in design and manufacturing technique operate first to the advantage of one system of electrification and then of another, there will always be controversy as to which system should have been chosen in any instance, but at no time in the past has it appeared that any one system showed so great an advantage over existing systems as to justify a large-scale change-over. Progress in railway electrification seems to depend more upon the concentrated development of the system which has been chosen in each instance rather than upon the development of new systems.

Diesel traction and battery locomotives have been mentioned as possible competitors with electrification, but their sphere of application appears to be complementary rather than competitive. In particular, Diesel and battery shunting locomotives are likely to be used to an increasing extent in conjunction with any large-scale electrification.

I have to mention a correction to Table 1 of the paper. Locomotive E.704 of the Paris–Orléans–Midi system was designed by La Société de Matériel Électrique S.W. (Schneider-Westinghouse), who also supplied a large part of the electric equipment. The remainder of the equipment was supplied by Forges et Ateliers de Construction Électrique de Jeumont.

THE MARCONI-E.M.I. AUDIO-FREQUENCY EQUIPMENT AT THE LONDON TELEVISION STATION

By I. L. TURNBULL, M.Sc.(Eng.), and H. A. M. CLARK, B.Sc.(Eng.), Associate Member.*

(*Paper first received* 19*th January, and in revised form* 12*th April*, 1939; *read before the* WIRELESS SECTION 3*rd May*, 1939.)

SUMMARY

The paper outlines the requirements of a high-quality sound equipment as supplied to the British Broadcasting Corporation for use in the London Television Station. Design features necessary to meet these requirements are indicated and a general description is given of the complete equipment. The final section of the paper gives information on the overall performance of the apparatus and includes data on the frequency and harmonic distortion of the amplifier equipment.

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CONTENTS—*continued.*

(1) GENERAL SCHEME AND SCOPE OF EQUIPMENT

(1.1) Introduction

During the course of development of high-definition television in the company with which the authors are associated, a certain amount of audio-frequency apparatus was in demand for demonstration purposes; as, however, the scope of television was rapidly widening, it seemed undesirable during that time to lay down any rigid specification for a complete system of audio equipment, which might have to be modified within a comparatively short period.

By 1934, however, the position had considerably clarified owing to the successful development of the Emitron camera. In 1935, when the Television Advisory Committee decided that a television station giving a public service would be set up at Alexandra Palace by the British Broadcasting Corporation and that television and sound programmes would be given from film and from studio, it became necessary to consider the audio-frequency requirements more definitely. A specification covering the overall performance was drawn up by the British Broadcasting Corporation, and the system described in the paper, and supplied for use at the

* Electric and Musical Industries, Ltd.

London Television Station, was designed to conform with this specification.

(1.2) Requirements

It was apparent that, although the single available studio was only of moderate dimensions, in order to give a continuous entertainment it might be necessary to accept programmes in sequence from several set-ups located in different parts of the studio. Further, it would be essential to provide facilities to fade from these programmes into sound from film or from gramophone records. Moreover, it was considered desirable to design the programme control equipment in two halves, which could be linked together as a single unit if necessary, each half being associated with one set-up. The sound balance controls having been preset at rehearsal, it would therefore only be necessary for the operator, at the conclusion of the programme from one set-up, to move over to the second set of controls to supervise the sound output from the other stage.

At the same time, in view of unknown conditions likely to be encountered during television development, it appeared essential to design the apparatus in such a manner that the equipment would be as flexible as possible.

(1.3) Performance Specification

The transmission of a high-definition television picture requires a wide frequency band, which in turn necessitates the use of an ultra-high frequency for the radiated carrier wave. It had been decided to transmit the accompanying sound on a similar ultra-high carrier frequency, namely $41 \cdot 5$ Mc./sec., or $3 \cdot 5$ Mc./sec. lower than the vision carrier frequency. This had the great advantage that it permitted interference-free receivers to be built in which the high-frequency circuits would not attenuate the sidebands, so that the higher audio frequencies could be reproduced at full value. The B.B.C. therefore specified that the main channel of the audio-frequency apparatus associated with the transmitter should have a frequency characteristic which should not deviate from flat by more than ± 2 db. over a frequency range of 40 to 10 000 cycles per sec. Moreover, a rather severe linearity specification was set, namely that the total harmonic production of any channel from microphone amplifier to input of transmitter should not exceed 1 % of the fundamental over the complete frequency range mentioned above.

(1.4) Reliability

In view of the fact that no previous experience was available in connection with the operation of high-definition television equipment and also that a high order of performance was necessarily demanded of many of the components in the vision apparatus, it was obviously desirable that the sound equipment should be as reliable as possible so that, in case of a vision breakdown, contact might always be retained with those receiving the programme. This requirement had considerable bearing on the design of the equipment, and in addition led to the provision of a considerable amount of stand-by apparatus, including both amplifiers and power supplies.

(1.5) General Arrangement of Apparatus

Fig. 1 gives a block schematic of the audio-frequency apparatus and shows the general arrangement of the equipment.

It will be seen that five moving-coil and three ribbon microphones, together with a similar number of associated " A " amplifiers, are provided. Two sound heads mounted on film projectors and two pick-ups associated with a gramophone desk, together with their " A " amplifiers, are also included.

The outputs of all the " A " amplifiers are brought up to jack panels on the sound control desk, which incorporates arrangements for fading and mixing eight channels. These eight sets of fade-and-balance controls are divided into two banks of four, the combined output of each bank being controlled in turn by a main fader potentiometer. The output from each of these main controls is then fed, via a special combining circuit, into two main amplifiers which raise the signal to a level sufficiently high for it to be fed directly to the sub-sub-modulator in the transmitter. By means of the combining circuit it is possible to feed the output from either main control into either of the main amplifiers, or alternatively to feed the combined main control outputs into either or both main amplifiers.

The output from each main amplifier is fed into the output distributor, where again it is possible to select either or both outputs to be fed to the transmitter. In addition, the output distributor divides the output from each of the main amplifiers into two channels, one to feed the transmitter and the other to feed the loud-speaker amplifier controls. The division is accomplished in such a manner that any load may be thrown on one channel without affecting the power transferred to the other in any way. Six loud-speaker amplifiers are provided which may be jumpered to the output distributor in such a manner that they may be fed from either or both main amplifiers at will.

Suitable metering arrangements are provided at the control position so that the programme level may be monitored by the operator. As an indication that the quality of the signals being radiated is satisfactory, a check receiver, fed from the sound aerial feeder, is supplied. The output from the check receiver is divided between two circuits, one of which provides an alternative supply to the control operator's headphones in place of that from the monitor panel, and the other of which is arranged to give the correct level to feed into the loud-speaker amplifiers.

It will be noticed that by throwing a 3-position key on the control desk, the operator may listen to outputs from (*a*) the monitor panel, (*b*) the check receiver, or (*c*) the fader check or " pre-hear " stud. The latter position enables the operator to listen to the output of any channel before he fades it into a programme channel.

In order that the producer may give instructions to the camera operators, suitable microphones and a talk-back amplifier are supplied.

Electrical testing equipment, consisting of an oscillator and gain set, is also provided, so that routine maintenance checks of amplifier gains and levels can readily be made. Testing of this description is rendered comparatively simple as, in order to ensure flexibility of the

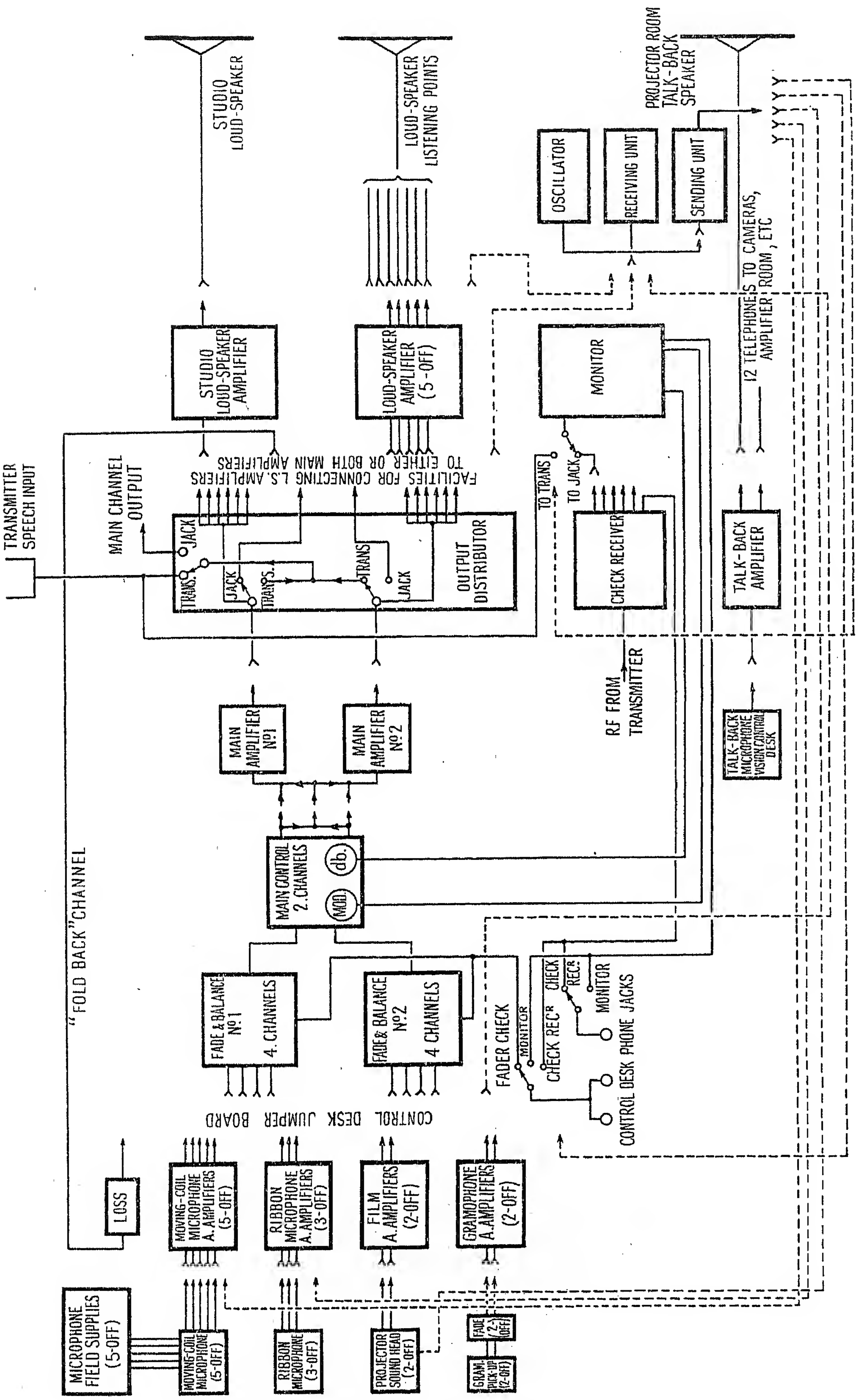

Fig. 1.—Block diagram of complete system.

equipment, the inputs and outputs of the component amplifiers, etc., are in general brought out to jacks so that any part of the apparatus is easily isolated. Testing circuits are shown dotted in Fig. 1.

(1.6) Operation of Equipment

The equipment may be used in any one of five ways, depending on the type of programme which it is desired to transmit.

When a simple transmission is required, any of the twelve "A" amplifier outputs may be connected to the four input channels of one of the fade-and-balance panels, while the output of the appropriate main control potentiometer is connected to the main amplifier which feeds the transmitter. The second fade-and-balance panel and main amplifier are then available as a stand-by channel, and may be connected at a moment's notice.

Secondly, as mentioned in Section (1.2), it may be required to transmit two completely separate transmissions consecutively, e.g. when using two sets in the studio, and where a quick change from one to the other is required. In this case the microphones, etc., appropriate to one set are connected to fade-and-balance panel No. 1, while those appropriate to the other set are joined to fade-and-balance panel No. 2. The outputs of the fade-and-balance panels may then be combined and fed through one main amplifier, leaving the other as a stand-by.

Thirdly, two completely independent systems can be arranged. For example, a transmission can be in progress from the studio through fade-and-balance panel No. 1 together with its associated main control with one main amplifier feeding the transmitter, monitor, and several loud-speakers. A rehearsal of gramophone or film sound may then be taken through the other fade-and-balance panel, main control, and main amplifier (which in this case has its output on the output distributor switched, not to the transmitter, but to the jack circuit). One or more selected loud-speaker amplifiers may be plugged to this particular main amplifier. In this case the two programmes will be completely separate from each other, with no chance of cross-talk or other interference.

Fourthly, the system may be operated in rather a specialized manner to cater for a condition that is peculiar to television. It is sometimes convenient to employ gramophone music as an accompaniment to a studio performance on occasions when an orchestra is hardly justified; examples of such are tap dancing and the accompaniment of instrumentalists, conjurers, etc. In this case it is necessary to pass the accompaniment to the transmitter and also to the performer in order that he may hear his accompaniment. In the case of television this is done by loud-speaker, since telephones would be visible in the picture. If a loud-speaker fed from the main channel were utilized for this purpose, trouble would probably arise due to acoustic feedback in the studio. This can be avoided by what has been called a "fold-back" circuit. In operation, the equipment is arranged as in the last method, giving two independent systems, the first system carrying the sound from the studio and the second taking the gramophone music. A loud-speaker, operating from a loud-speaker amplifier connected to the second main amplifier, supplies the accompaniment to the performer in the studio, while another output from the same main amplifier is "folded back" through an attenuator, shown as "Loss" in Fig. 2, and fed through one of the controls on fade-and-balance panel No. 1 into the main studio programme. Owing to the method of mixing employed on the fade-and-balance panels, there can be no cross-talk between the various inputs, so that there is no possibility of a "howl-back," no matter what gain is used in the channel.

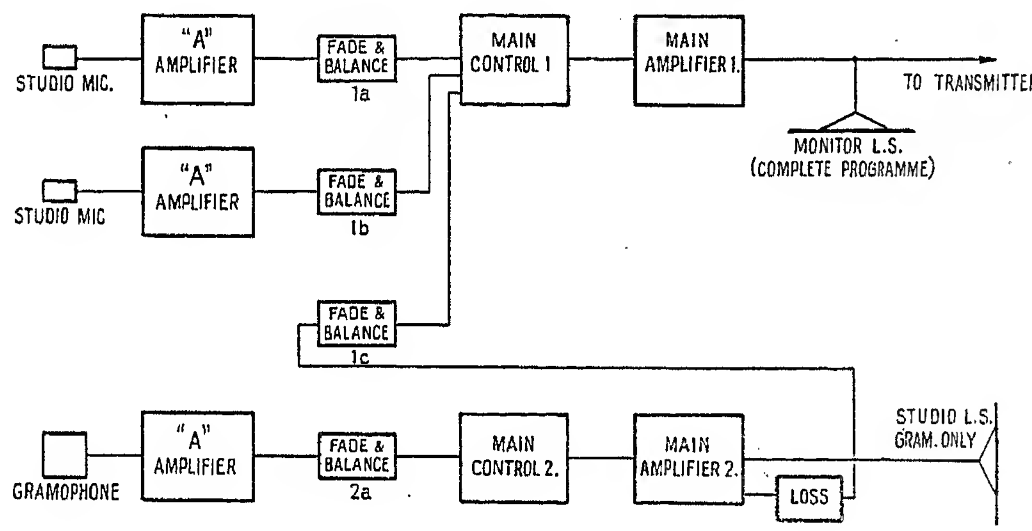

Fig. 2.—Block diagram of apparatus arranged for "fold-back" transmission.

Lastly, when handling a big production it is sometimes desirable to be able to control with one main fader more than four microphones or other sources at once. This is accomplished by employing a similar arrangement to that described above as a "fold-back" circuit. In place of the gramophone, however, four of the microphones are connected to fade-and-balance panel No. 2, and after amplification in main amplifier No. 2 the combined output is folded-back to one of the inputs on fade-and-balance panel No. 1. The other three inputs of this fade-and-balance panel may be connected to three further microphones and the combined output taken through main control No. 1 and main amplifier No. 1 to the transmitter. By this means it is possible to handle the outputs of seven microphones or other sources on main control No. 1.

Plate

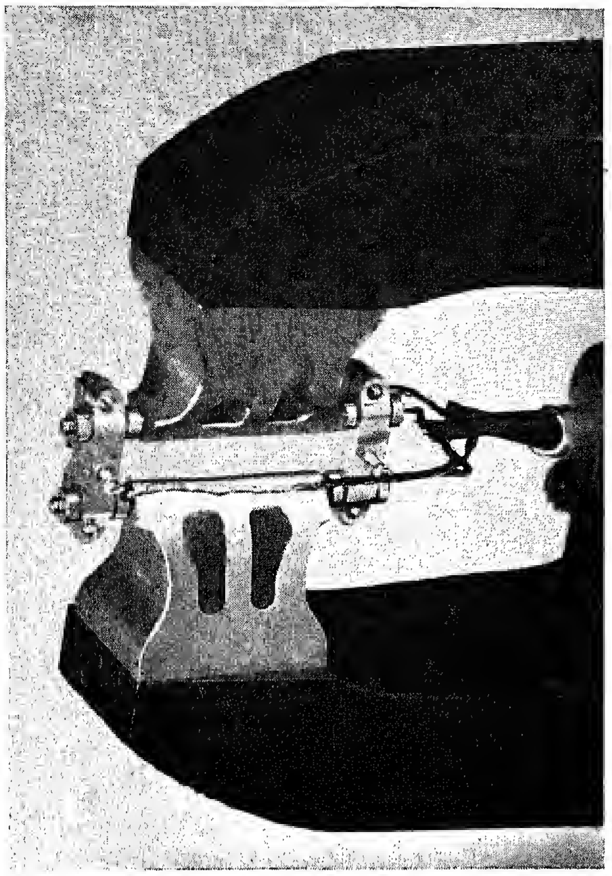

Fig. 8.—Pole-piece and ribbon assembly of ribbon microphone.

Fig. 4.—External view of moving-coil microphone.

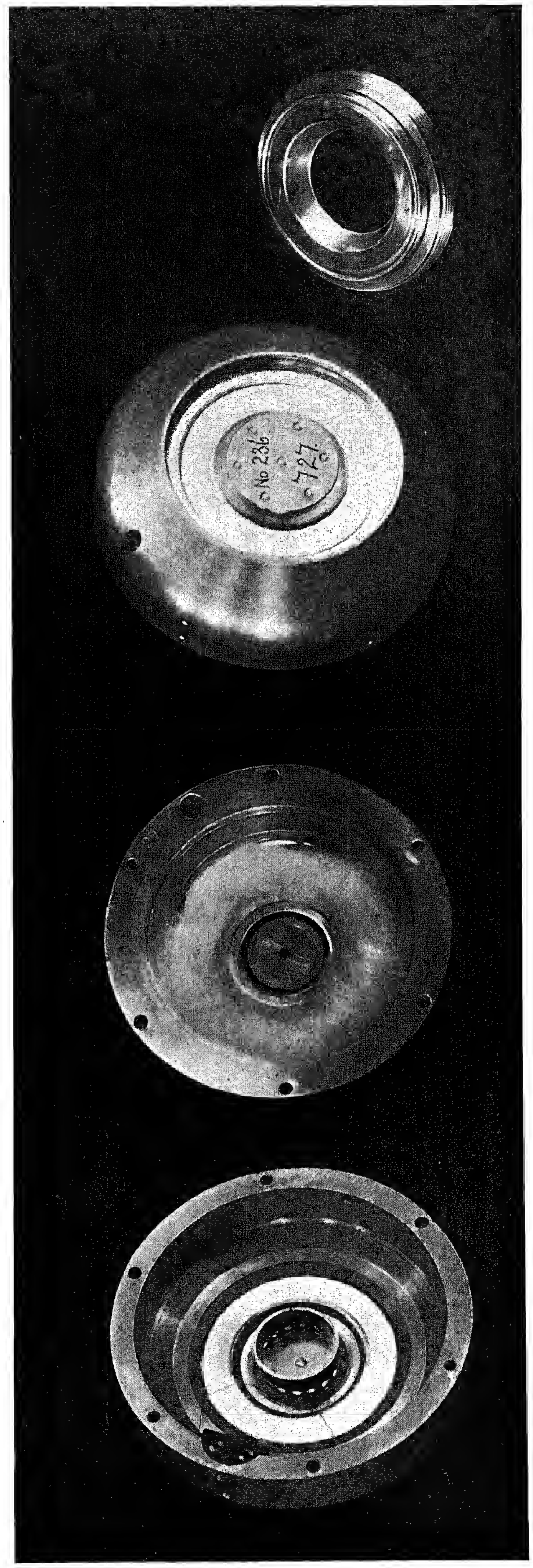

Fig. 5.—Moving-coil microphone disassembled.

In order that such a variety of circuit arrangements may be used, in some of which more amplifiers are operated in cascade than in others, it is necessary to keep the tolerances in frequency characteristics of the individual amplifiers below that permissible where a constant set-up of equipment is used.

(2) DESIGN AND CONSTRUCTION OF EQUIPMENT

(2.1) Microphones

In view of the variety of acoustic conditions likely to be encountered in the transmission of television programmes either in studios or the open air, it was felt that both pressure and velocity microphones would be necessary.

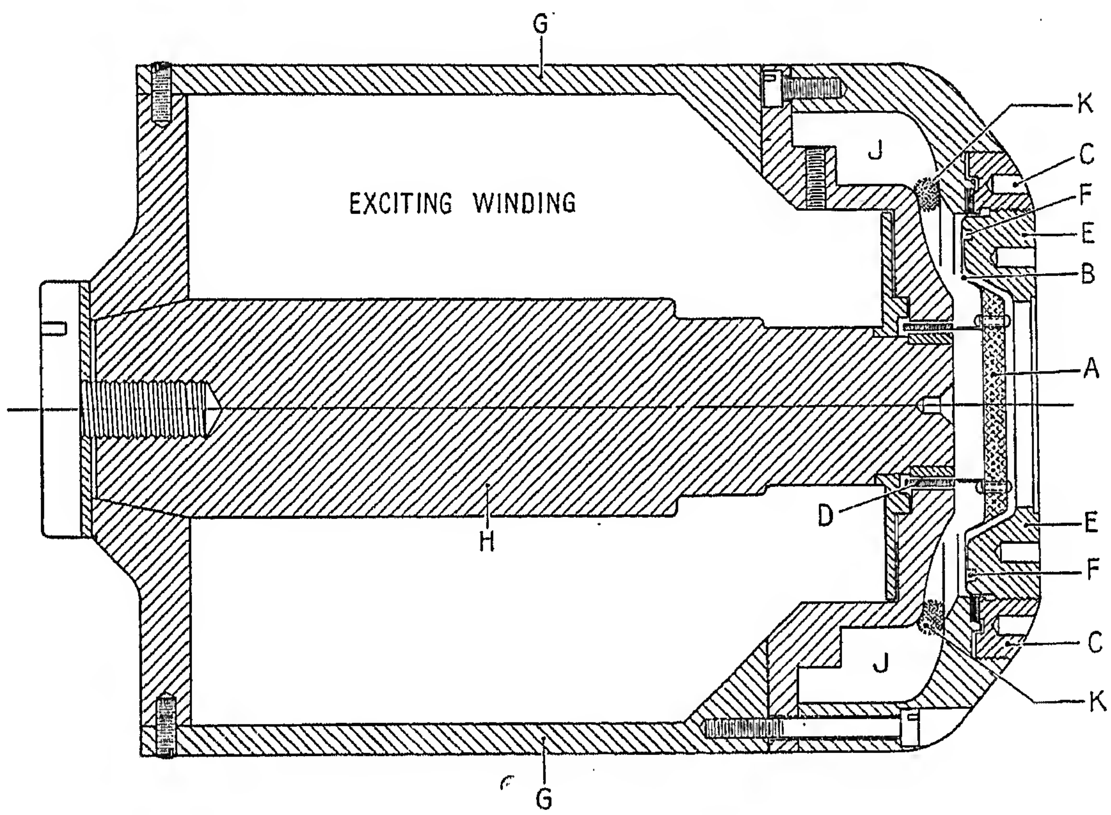

Fig. 3.—Sectional drawing of moving-coil microphone.

(2.11) Pressure-type microphones (moving coil).

About 9 years ago a high-quality moving-coil pressure-operated microphone was developed for use in sound recording. This microphone has proved so successful in practice, both as regards electrical performance and reliability, that the same type of microphone has been employed for television studio work. A description of this microphone has been given elsewhere by the inventors,* but for completeness the main outlines will be repeated here.

(2.111) *General principles.*

The microphone consists essentially of a rigid piston diaphragm to which is attached a light coil moving in a magnetic field. The mechanical resonance of the moving system is controlled by electromagnetic damping, which is obtained by applying across the terminals of the moving coil a shunt electrical circuit whose impedance is low at the frequency of mechanical resonance, but high at frequencies above and below it. A suitable circuit consists of an inductance, capacitance, and resistance in series, the inductance and capacitance resonating at the mechanical resonance frequency of the microphone. Movement of the coil in the magnetic field at this frequency will then produce a comparatively heavy current which will tend to oppose the motion of the coil. In order to obtain complete equalization of the output of the microphone both in magnitude and in phase, the values of inductance, capacitance, and resistance in the shunt circuit are arranged to have the same ratio as the mass, compliance, and damping of the mechanical system in the neighbourhood of resonance.

(2.112) *Mechanical design.*

An outline drawing showing the construction of the microphone is given in Fig. 3. Fig. 4 (see Plate, facing page 442) shows the external appearance, and Fig. 5 (see Plate) shows the microphone disassembled.

In order that the diaphragm (A) may act as a rigid piston over the acoustic frequency range, it is made in composite form comprising a layer of Balsa wood about 2·5 mm. thick enclosed on each side by thin aluminium sheets, the whole being riveted and waxed together to form a rigid structure. An extension of one of the aluminium sheets, forming a surround (B) to the diaphragm proper, is used as a support and is clamped by a screwed brass ring (C) to the body of the microphone. The coil (D), which is of enamelled aluminium wire, is wound on a thin aluminium former which is in turn riveted to the Balsa-wood diaphragm; the whole assembly is therefore exceedingly rigid and light, the mass of the combined coil and diaphragm not exceeding 0·75 g.

To enable the diaphragm surround to be relieved of any irregularities or tendency to "kettle bottom," a stretching ring (E) is fitted to the inside of the clamping ring (C) mentioned above. By rotating the stretching

* See British Patent No. 350998 (A. D. Blumlein and H. E. Holman).

ring the surround is stretched perfectly flat so that the diaphragm will move in proportion to varying sound pressure; at the same time rotation of the stretching ring forms a convenient method of adjusting the frequency of the overall mechanical resonance of the system. Experience has shown that, in general, the use of a diaphragm which is not under an initial radial tension may lead to small instabilities in performance. To avoid trouble due to the thin diaphragm surround itself being excited into a high-frequency resonance and probably modifying the motion of the main diaphragm, the body of the stretching ring is so shaped as to shield the surround from sound waves impinging on the front of the microphone. In addition, to damp out any parasitic surround resonance which might be excited, the inner face of the stretching ring is brought very close to the surround surface in order to provide air-viscosity damping on the latter. Still greater damping is obtained by the presence of a small cavity or groove (F) cut into the surface of the stretching ring immediately inside the stretching ridge; movement of the surround then forces air through the narrow channel between stretching ring and surround into the groove beyond.

The magnetic system of the microphone consists of a small pot magnet (G), forming the main body of the instrument. The centre pole of the magnet (H), in view of the high flux density which it is called upon to carry, is constructed of cobalt iron* and is so shaped that the leakage flux is reduced to a minimum. More recent microphones are fitted with permanent magnets; here again, the magnet forms the main body of the instrument, the centre pole-piece remaining of cobalt iron.

In view of the extreme lightness of the diaphragm assembly and the desirability of keeping the main resonance frequency of the system at a convenient equalizing frequency, say 500 cycles per sec. or lower, it is essential to avoid the presence of a high air stiffness acting behind the diaphragm. It is therefore necessary to provide a cavity (J) behind the diaphragm to reduce the air stiffness to a minimum, meanwhile preventing any Helmholtz-resonator effect in the cavity by the insertion of a ring of loose cotton wool (K) at the mouth.

After its various component parts have been assembled, the microphone is adjusted in the following manner. Using an average value of microphone field excitation, the frequency of zero motional reactance of the moving coil, corresponding to the natural resonance frequency of the diaphragm assembly, is determined by means of an a.c. bridge and variable-frequency oscillator. The diaphragm resonance frequency is then adjusted to approximately 500 cycles per sec. by a slight rotation of the diaphragm stretching ring, which causes a greater or less tension to be applied to the diaphragm surround. The value of the alternating current supplied to the microphone from the bridge is next varied over a range of 30 db., covering the most important part of the range of diaphragm amplitudes likely to be encountered in practice, and any change of resonant frequency noted. In a good microphone this change should be very small; if it is not small, the diaphragm surround is stretched over its elastic limit and the test repeated. Usually a single such stretching suffices to give a linear result.

* An alloy of high magnetic saturation, known commercially as "D.C.I."

In order that any microphone may be used with any equalizing circuit, the ratios of mass, compliance, and damping of the moving system are kept constant for all microphones. The mass of the diaphragm assembly is fixed during manufacture and the compliance is adjusted as described above; the damping is then fixed by adjustment of the magnetic field, which, in turn, is controlled by the value of the exciting current.

The length of the microphone, excluding terminals, is 4 in. and the diameter is $2\frac{3}{4}$ in.

(2.113) *Equalizer.*

In practice, the equalizer or shunt circuit already mentioned is located in the associated microphone amplifier, being connected to the microphone itself by means of a low-resistance cable. Owing to the fact that the moving coil of the microphone cannot satisfactorily be wound to a high impedance it is not feasible to connect the shunt circuit, consisting of inductance, capacitance, and resistance in series, directly across the coil since the value of the necessary capacitance becomes unduly large. To overcome this difficulty the electrical output from the moving coil is fed into the low-impedance winding of a three-winding step-up transformer, the second of whose windings provides a suitable impedance (approximately 1 000 ohms) for the equalizing circuit and the third winding of which provides a still higher impedance for connection to the grid of a valve. In order to compensate for the increased impedance of the microphone moving coil at high frequencies, a condenser and resistance are shunted across the inductance of the simple equalizer; further, to attenuate the heavy low-frequency transients occasioned by unvoiced and explosive sounds in speech which cause overloading trouble, a resistance is shunted across the equalizer capacitance which has the effect of reducing the microphone output at frequencies below 50 cycles per sec.

(2.114) *Field-current supply.*

Direct current to supply the winding in the directly excited type is obtained from the a.c. mains by means of a Westinghouse bridge rectifier. Very complete smoothing of the rectified output is essential in order to avoid the introduction of hum into the microphone moving coil, which works at an exceedingly low electrical level.

(2.115) *Cross-talk from camera cable.*

During early operation in a television studio it was found that noticeable cross-talk existed between the Emitron camera cable, carrying the 10 000-cycle scanning currents, and the screened and twisted microphone cable, due to induction between isolated loops in the twist of each cable.

The difficulty was overcome by introducing a third lead between the two microphone leads, and using this third lead as one conductor to the moving coil and the original two outer leads in parallel as the other conductor; this, in effect, produced an astatic arrangement.

(2.116) *Performance.*

Fig. 6 shows the overall frequency response of a microphone with its amplifier for sound arriving normal

to the face of the microphone and also for sound arriving in random directions.

It will be seen that for random sound the frequency response is flat to within $\pm$ 1·5 db. between 40 and 10 000 cycles per sec.

The response of the microphone, combined with the 3-stage microphone amplifier supplied, is approximately

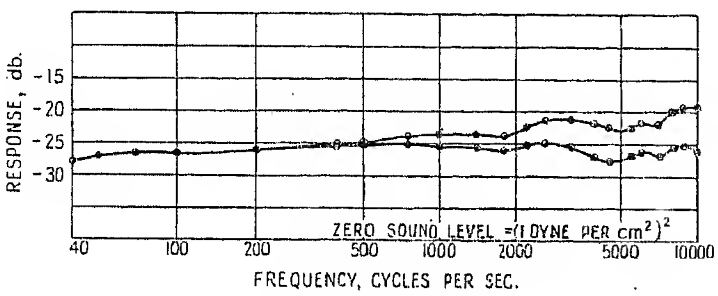

Fig. 6.—Frequency response of moving-coil microphone with "A" amplifier.

The upper curve applies to sound arriving along the axis of the microphone, the lower shows the response to random sound.

— 26 db.* for random sound. The response of the microphone alone at 500 cycles per sec. is — 69 db.

The polar characteristic of the microphone is shown in Fig. 7. From this it will be noticed that the response of the microphone to frequencies below 1 000 cycles per sec. is substantially circular. Above this frequency, sound arriving at the rear of the microphone produces a relatively smaller response, although it will be observed that, owing to the comparatively small diaphragm, even at 7 000 cycles per sec. the loss for sound arriving at 90° to the face-on position is only 8 db.

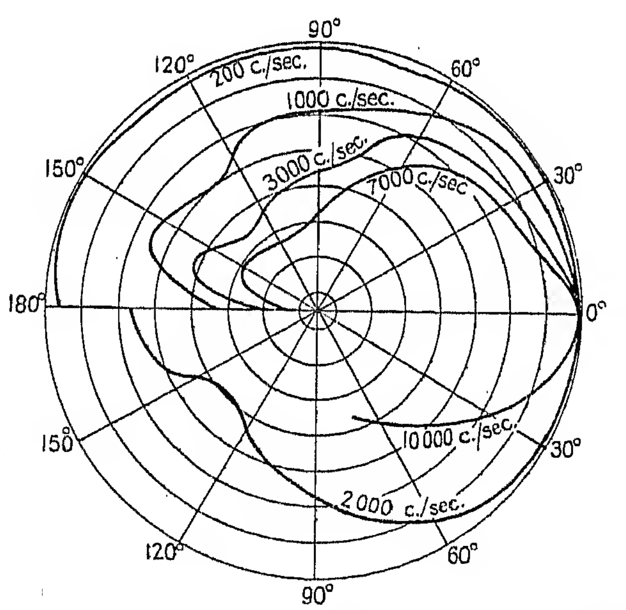

Fig. 7.—Polar diagram of moving-coil microphone.

The ordinates give the output voltage with respect to that due to a wave arriving in the direction of the axis.

As described in Section (2.112), the change of resonant frequency of the diaphragm assembly is determined when the amplitude of vibration of the diaphragm is varied over a range of 30 db. Should this change exceed 0·5 % the microphone is returned for further adjustment; in the majority of cases the frequency-change is considerably smaller than this, being of the order of 0·05 % or less.

* See Section (3.1) for an explanation of response and level rating.

In practice, the microphone has been found to be exceedingly robust; several times microphones have been accidentally dropped from such a height as to shear off a brass terminal without affecting their acoustic characteristic. Moreover, their stability of response is maintained over long periods; apart from occasional slight adjustment of the stretching-ring position required to re-establish their resonant frequency, a considerable number of microphones have been operating satisfactorily without attention or change of characteristic since they were first constructed in 1931.

The frequency response of each microphone is tested before issue, and any microphone not conforming to the required frequency response over the range 30–10 000 cycles per sec. within $\pm$ 1·5 db. is rejected. This requirement enables microphones to be interchanged indiscriminately without noticeable change of speech quality.

(2.12) Velocity-type microphone (ribbon).

These microphones are provided to enable certain types of work to be done which require a directional microphone characteristic. The design of the microphone follows conventional lines except that the ribbon is shorter than those commonly employed. Fig. 8 (see Plate) shows the pole-piece and ribbon assembly.

(2.121) *General description.*

A thin uncorrugated aluminium ribbon, approximately 0·00005 in. thick and 1 in. long, is suspended between the poles of a permanent magnet of conventional design. Adjustment is provided to alter the longitudinal tension on the ribbon, and so control its natural resonance frequency, by means of nuts on the pillars supporting the ribbon clamps. At the bottom of the magnet is fixed a small shielded transformer which raises the impedance of the ribbon from approximately 0·25 ohm to 200 ohms, a suitable value for connecting to a line and a microphone amplifier. The primary of this transformer is wound with 9-strand wire to avoid the use of large-diameter solid wires, which are difficult to wind in small transformers and give rise to eddy-current losses. The ribbon is protected by means of a metal gauze covering, inside which is mounted a silk draught screen.

In case it should be necessary to use the microphone close to a sound source, with a consequent increase in low-frequency output, a bass cut, controlled by a switch, is incorporated in the microphone amplifier. Further details of this arrangement are given in Section (2.32).

(2.122) *Performance.*

The frequency response of the microphone with sound arriving normal to the ribbon is shown in Fig. 9. It will be seen that over the range 35–10 000 cycles per sec. the deviation from flatness does not exceed $\pm$ 3 db.

The response of the microphone for an r.m.s. sound pressure of 1 dyne per cm^2 normal to the ribbon is approximately —81 db.; this corresponds to an e.m.f. of 8×10^{-5} volt.

The microphone has the well-known velocity polar diagram, i.e. approximately two spheres with the plane

of the ribbon tangential to the point of contact of the spheres. This diagram is modified slightly at the higher frequencies in that the spheres tend to become ellipsoidal.

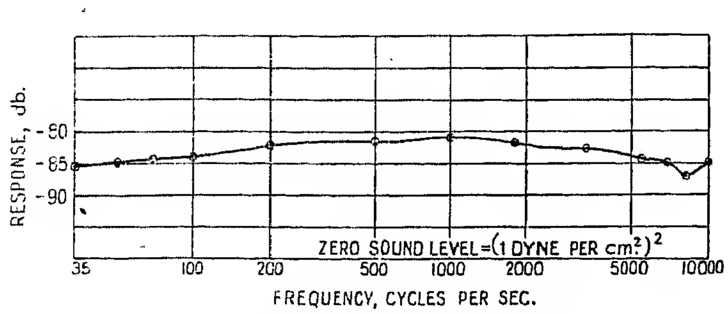

Fig. 9.—Frequency characteristic of ribbon microphone (axial direction).

It will be noticed, however, from Fig. 10 that even at 10 000 cycles per sec. the deviation is small in the horizontal plane, while owing to the shortness of the

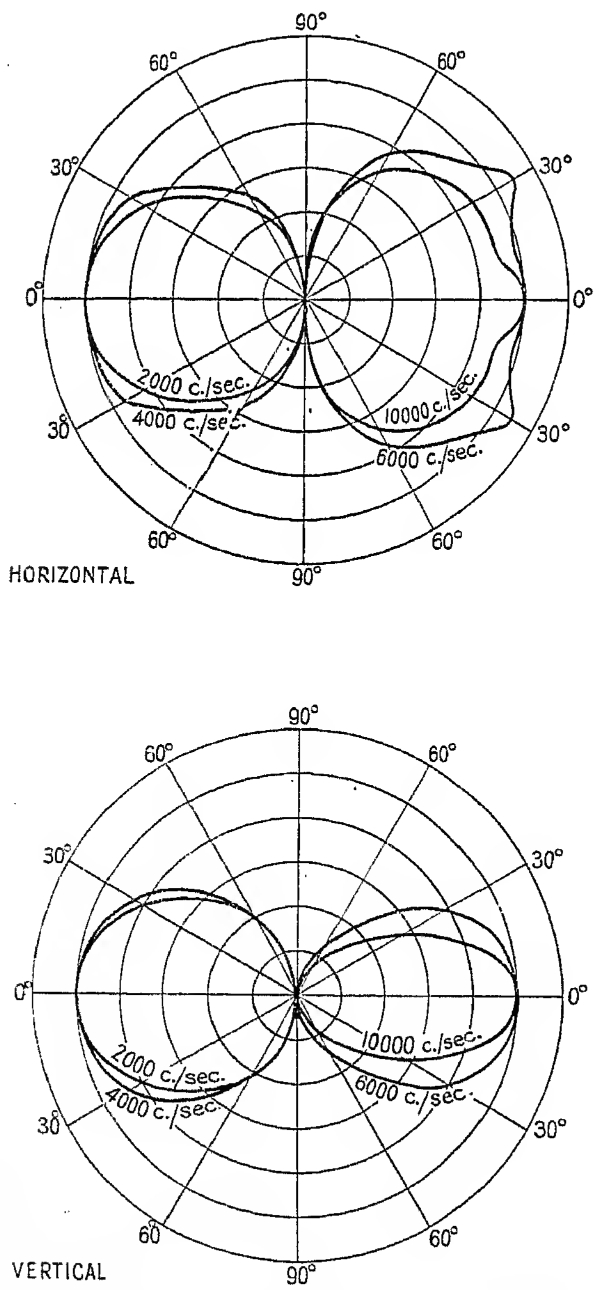

Fig. 10.—Horizontal and vertical polar diagrams of ribbon microphone.

The upper curves apply to azimuth angles and the lower to elevation when the ribbon is in a vertical plane.

ribbon employed it is only above 6 000 cycles per sec. that the vertical polar characteristic becomes appreciably distorted. Reduction of this type of distortion is desirable when the microphone is used opposite a source subtending a vertical angle, e.g. an orchestra on a stepped platform, or when the microphone has to be used above the source of sound, as is necessary when transmitting from a televised scene where it is essential to use a boom and to exclude the microphone from the picture.

(2.2) Recorded Sound

(2.21) Gramophone.

The gramophone desk, which is of conventional design, is equipped with stroboscopically marked twin turntables. Magnetic induction between the electric driving motors and the pick-up windings is reduced by the provision of mumetal screens fitted immediately below the turntable. Cueing indicators, to enable selected portions of a record to be interpolated into the programme at the correct moment, are also provided. The indicators are sufficiently sensitive to enable a selected spot on a rotating record to be located within one groove pitch.

The pick-up employed has one or two outstanding features. The armature, consisting of a thin steel tube, is provided with a V groove at its lower end enabling the needle to be gripped without the use of a needle screw. The armature is supported by a thin phosphor-bronze blade so positioned that little constraint is

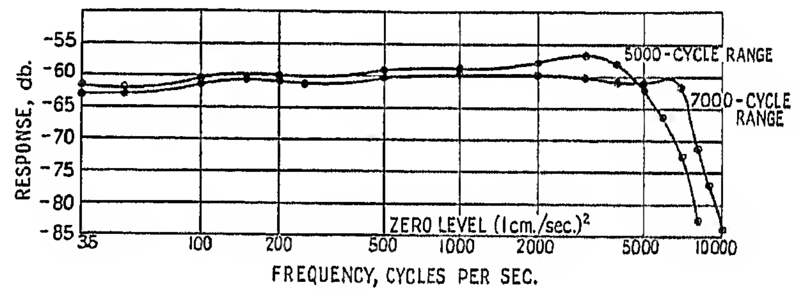

Fig. 11.—Alternative frequency response of gramophone-desk circuits, allowing for constant-amplitude recording characteristic for the low frequencies.

exercised on lateral movements of the armature, but motion in a direction parallel to the record groove is considerably restrained; a considerable amount of distorted reproduction has been traced to unauthorized movement in the latter direction. Both armature and blade are surrounded by a highly loaded rubber.

In order to compensate for the bass cut which is introduced into all lateral-cut gramophone records for well-known reasons, an equalizer is necessary. To render any equalizing more simple and flexible the pick-up is first of all built out to a constant resistance by means of a series and shunt arm containing resistances and condensers. The necessary components are then introduced to restore the bass cut mentioned above, and following this is a circuit designed to reduce the frequency range of the pick-up to a nominal 5 000-cycle cut-off: without this circuit in use, the natural cut-off of the pick-up is of the order of 7 000 cycles per sec. The object of this circuit, which may be inserted by means of a key mounted on the front panel of the desk, is to reduce surface noise, at the expense of high-frequency response, from records which are not of the highest quality. Finally, the pick-up output is fed into a

resistance fader which is incorporated on a panel mounted in front of the operator.

As will be seen from Fig. 11, the full range characteristic from a standard-frequency record is flat to within $\pm$ 2 db. from 35 to 7 000 cycles per sec.: with the key in the 5 000-cycle position there is a loss of approximately 10 db. at 7 000 cycles per sec.

(2.22) Film sound.

Two film projection machines are provided as part of the station equipment so that a continuous programme of film may be radiated if desired. The machines are standard theatre projectors and were equipped with sound heads; as operated normally, however, the latter, although capable of good commercial quality, were not quite of the class required for high-quality broadcasting, and several modifications have been made.

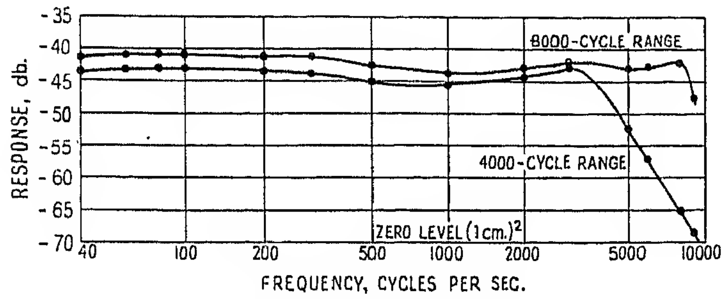

Fig. 12.—Alternative frequency response of film projection sound-head circuits.

As finally installed, each sound head is equipped with a photocell whose output is fed to a transformer which in turn is connected to the film " A " amplifier. The transformer, which is elastically mounted to avoid pick-up due to machine vibration, is purposely wound with a high leakage inductance, which is resonated with a preset condenser contained in the sound head. By this means it is possible to obtain a frequency characteristic which has not fallen appreciably by 8 000 cycles per sec., although by operating a key which cuts out the preset condenser the higher frequencies are considerably depreciated. The latter characteristic, which is employed on films where the recording is not of the highest quality, commences to fall at 4 000 cycles per sec. and is about 20 db. down at 9 000 cycles per sec.

Frequency characteristics are obtained as shown in Fig. 12 using a standard-frequency film record and a light slit 0·6 mil wide. As will be seen, the frequency response with the key in the " 8 000 cycles per sec." position is flat to within $\pm$ 2 db. from 40 to 9 000 cycles per sec.

The polarizing voltage required for the photocell operation is supplied from a stabilized rectifier source (mentioned in Section 2.8) and is fed to the photocell anode through a decoupling unit.

(2.3) Amplifiers

There are 21 amplifiers in the equipment. The general design of all of them being largely conventional, only a brief description of the amplifiers themselves will be given here. This will be followed by a discussion of the design considerations which were necessary to meet the specification, and reference to particular amplifiers will be made by way of example.

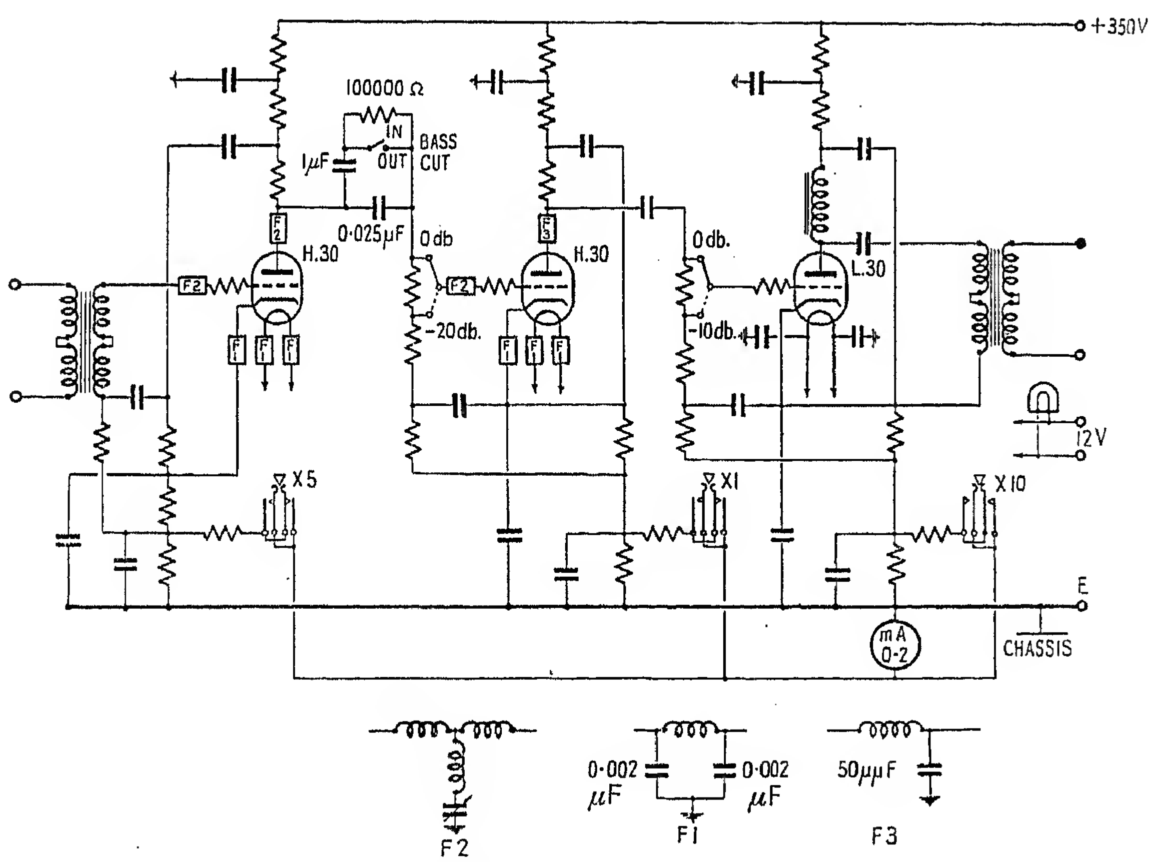

Fig. 13.—Circuit of ribbon microphone " A " amplifier.

(2.31) Amplifier types.

The types of amplifier used in the system fall into three general groups. The microphone or " A " amplifiers, of which 12 (including film and gramophone channels) are shown in Fig. 1, are required to raise the level up to 1 milliwatt, which is the input level of the mixing circuits. A typical " A " amplifier circuit (actually that of a ribbon microphone amplifier is shown in Fig. 13.

Since the sound level at the microphone may vary considerably for different types of programme, it was considered advisable to include in the amplifier a coarse gain adjustment in the form of two grid potentiometers. For normal studio use the amplifier is used with 20 db. less than its maximum gain, which is about 80 db. The bulk of the gain is provided by the first two stages. The third valve is capable of supplying the normal output of zero level (1 milliwatt)* with a considerable overload capacity.

The second group of amplifiers consists of the two main amplifiers (Fig. 14) which are required to bring the output of the control-desk circuits up to a distribution level of + 22 db. Since the output level of the mixing circuits to enable components to be changed without altering the frequency characteristic within the operating range.

As the circuits connecting the amplifiers are all of 200 ohms impedance, input and output transformers are used for all amplifiers. In the case of input transformers the secondaries are not loaded by shunt resistances. The step-up is not very great and the main inductance is made high, so that the effective input impedance to the amplifier as seen on the primary side is very high compared with 200 ohms throughout the working frequency range. A type of winding is used which enables the leakage inductance to be kept down to 1/3000 of the main inductance, with a secondary capacitance of about 30 $\mu\mu$F when the primary is earthed. In this way the

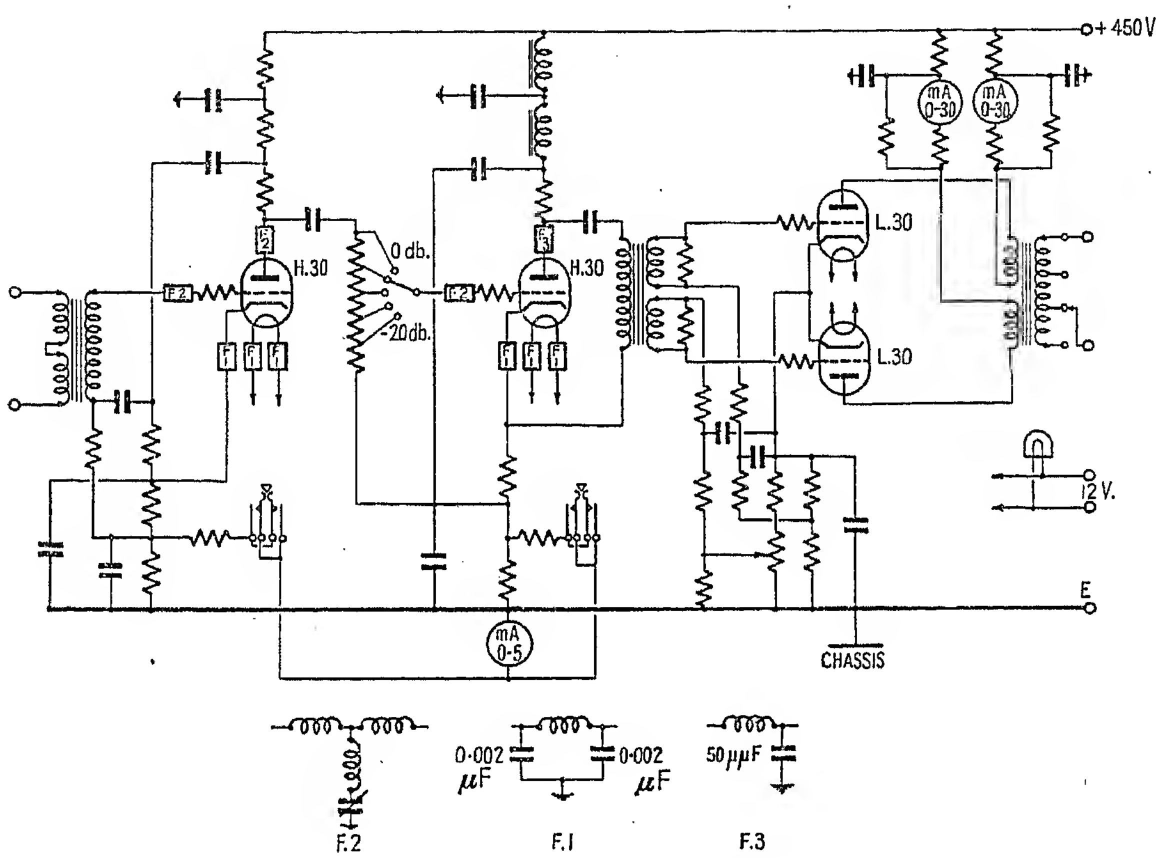

Fig. 14.—Circuit of main amplifier.

is commonly quite low, the first stage is similar to that of an "A" amplifier. In order to supply the greater output level, however, the final stage is of the push-pull type.

The third amplifier group contains the loud-speaker amplifiers, which are described in Section (2.64).

(2.32) Frequency characteristic.

The general principle of maintaining a very level frequency response for each individual amplifier has been necessarily adopted in order to allow for the interchange of amplifiers which is demanded by the use of the various set-ups described in Section (1.6).

Similarly the compensation of a loss in one part of an amplifier by a corresponding gain in another part of the circuit has not been applied to any great extent. This has in turn involved what amounts to an extension of the frequency range, since the losses due to such factors as valve capacitance and the capacitance and inductance of transformers, have of necessity been made low enough

* See Section (3.1) for an explanation of response and level rating.

resonance of the leakage inductance and the secondary capacitance (including the input capacitance of the valve) is kept well above the working frequency range. This resonance is damped chiefly by the primary load, together with some additional series grid resistance where necessary. The substantially open-circuit input impedance which the amplifiers thus have is an important feature in the design of the control-desk circuits, and also enables the full open-circuit voltage to be obtained from ribbon microphones, etc. Moreover, the absence of loading resistance on the input transformer gives the maximum ratio of signal to noise in the grid circuit. A further feature of this type of input-circuit design is that a wide range of primary load impedances can be covered without appreciably changing the frequency characteristic.

The anode load of all first-stage valves is purposely kept low in order to reduce the effective input capacitance. The effect of the latter is so low that with commercial valve limits no appreciable change of frequency characteristic occurs when a valve is changed.

Intervalve coupling for balanced stages is by trans-

former. Particular care has been taken to prevent any signs of "in-phase" resonance of the secondaries which would produce an unbalance of the valves at high frequencies.

The series condensers feeding transformer primary windings are not made so small as to maintain the bass response by resonance, as it is considered that this practice encourages the production of low-frequency 3rd harmonics by the core.

The design of the output transformers is such that a lower ratio of leakage inductance to main inductance is obtained than in the case of the input transformers, at the expense of the greater capacitance which is tolerable. This ratio is approximately 1/5000 in the case of "A" amplifier output transformers. It is desirable to maintain an output impedance which is substantially resistive throughout the frequency range; this is particularly so in the case of the main amplifier which terminates the output distribution circuit. Secondary taps are provided on the output transformer to obtain a good 200 ohms' impedance with any output valves within commercial limits, but these have not been needed in practice.

Resistance coupling with fairly long time-constants is used between most single-valve stages. In a few cases a very small low-frequency rise, generally not more than 0·2 db., is introduced in the anode first decoupling circuits to compensate for grid-circuit and other low-frequency losses. In all cases, however, care is taken to ensure that below the normal frequency range the gain does not rise, but steadily decreases.

As already described in Section (2.121) of the paper, the ribbon-microphone amplifiers have an optional bass cut consisting of a reduced grid-circuit time-constant which produces about 5 db. loss at 100 cycles per sec. The shunt resistance shown in Fig. 13 serves to keep the larger condenser charged, to avoid switching clicks.

In the case of "A" amplifiers for the moving-coil microphones, an equalizer is connected to a third winding on the special input transformer, as has already been described in Section (2.113).

The variation of gain with frequency for all except the moving-coil microphone "A" amplifiers is very small. A manufacturing tolerance of $\pm$ 0·2 db. maximum departure from the gain at 1 000 cycles per sec. is allowed from 40 to 10 000 cycles per sec. The maximum change in the gain relative to 1 000 cycles per sec. due to adjustment of the preset grid potentiometers in amplifiers is also $\pm$ 0·2 db. These figures apply to the main amplifiers and to all "A" amplifiers except those for moving-coil microphones. The latter are required to conform within the same tolerances to a theoretical equalizer characteristic when tested from an input circuit whose impedance simulates that of a microphone.

(2.33) Harmonic distortion.

Where possible, the reduction of non-linear valve distortion is achieved by the simple expedient of using triodes with high anode loads. In the case of the first stages, where a low load is used, it was found desirable even in spite of the low operating levels to utilize a small negative feedback. The use of a simple cathode resistance was debarred by considerations of heater hum, so the arrangement shown in Fig. 13 was adopted. Unless the distortion due to the first two stages is made small compared with that of the output stage, it is found that the total 2nd harmonic will vary between wide limits as the setting of the inter-stage potentiometers is altered, producing almost complete cancellation in some cases.

The output valves of the "A" amplifier are required to supply a nominal power of 1 milliwatt to a matched load. A large overload factor is desirable at this point, and hence an L.30 valve is used which will supply considerably more than 1 milliwatt without serious distortion.

In the case of the main amplifier (Fig. 14) the output stage consists of two L.30 valves in push-pull, as a maximum output of + 22 db. (160 mW) is required. Since this power will fully modulate the transmitter, it is a definite maximum value and a very high overload capacity is unnecessary.

The odd-harmonic distortion produced by overloading of transformer iron is a function not only of the voltage level but also of the shunting loss which the core produces in the circuit. It will be appreciated that if the low-frequency shunting loss is made small by the use of a high inductance, not only is the flux density reduced, with consequent reduction in the change of permeability and power loss of the iron, but the effect of these changes on the circuit is also reduced. Thus the use of a type of transformer winding which gives a low ratio of leakage inductance to main inductance is indirectly an aid to harmonic reduction at the low frequencies.

The even-harmonic distortion in amplifiers is substantially constant with frequency, originating almost entirely in the valve, while the odd-harmonic distortion is most apparent at the low frequencies. Owing to the difficulty of measuring low values of distortion, particularly at low frequencies, the figures are given in the form of harmonic production rather than in the form of intermodulation products. In the case of the "A" amplifiers, difficulty was sometimes experienced in making reliable measurements of harmonics of less than 0·25 %, reckoned on a current basis, at an output level of 1 milliwatt fundamental. The Table shows some harmonic-distortion figures for representative amplifiers. The figures give the magnitude of the harmonic current as a percentage of the total output. The valves used for the tests were average samples.

(2.34) Noise.

The choice of the first valve from the point of view of noise depends upon the following features:—

(a) Anode-circuit noise to be low compared with the thermal noise from the grid circuit.

(b) The available gain to be high enough to eliminate noise from the succeeding stage.

(c) Low heater noise.

(d) Low microphony.

The type of valve chosen (H.30, Marconi-Osram) appeared to satisfy these conditions better than any other, including those specially made for low noise. The anode-circuit noise for an average H.30 operating at 3 mA is equivalent to the thermal noise of 1 200 ohms in the grid circuit, which is well below the effective grid-

circuit impedance. The mutual conductance at this anode current is 4 mA per volt, while the heater noise has been reduced to a very low value due to (*a*) use of a non-inductive heater operating at a low current, (*b*) the grid being brought out at the opposite end of the bulb to the heater leads, and (*c*) the careful screening of the heater leads as they emerge from the pinch. As already mentioned, however, it is necessary to keep the cathode at earth potential. The H.30 is also satisfactory from a microphonic point of view, provided care is taken in the design of the mounting.

Table

Harmonic-distortion Levels of Various Types of Amplifiers in the System*

Amplifier	Output level	1 000-cycle fundamental		40-cycle fundamental	Remarks
		Percentage 2nd harmonic	Percentage 3rd harmonic	Percentage 3rd harmonic	
Ribbon mic. amplifier	db. 0	0·5	< 0·25	—	Max. gain
Ribbon mic. amplifier	0	< 0·25	< 0·25	0·14	Min. gain
Moving-coil mic. amplifier ..	0	0·45	< 0·25	—	Max. gain
Moving-coil mic. amplifier ..	0	< 0·25	< 0·25	0·14	Min. gain
Main amplifier	+ 20	0·14	0·16	0·2	Normal gain
Complete programme channel..	+ 15	0·5	< 0·15	0·66	Normal conditions

* The harmonic distortion is expressed as a percentage of the total output current.

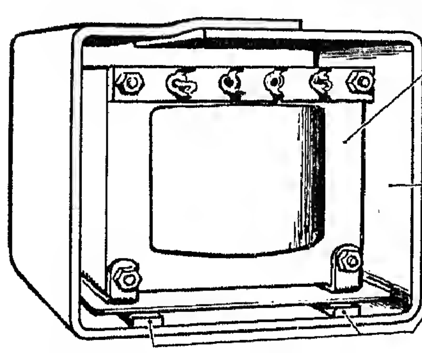

Fig. 15.—Mumetal ring for doubly shielded low-level transformers.

Rather elaborate precautions were taken to avoid microphony, as the amplifiers were required to operate in a situation where the racks were likely to be touched during transmission and where a comparatively high noise-level might be encountered. Firstly, the complete chassis on which all amplifier components are mounted is sprung by fairly stiff rubber supports from the main panel framework. Secondly, the first- and second-stage valveholders are as flexibly mounted on the chassis as is feasible in view of the fact that the valves work horizontally. In order to overcome air-borne microphony in the first stages, lead screens about $\frac{3}{16}$ in. thick are used to cover the valves.

Another source of noise is induction from a.c. power sources. The equipment is laid out so that all low-level input transformers are in a bay at the opposite end to the bays carrying the mains transformers. Even so, it is necessary to take special precautions to keep the magnetic pick-up value below that of the heater hum. All low-level transformers are screened in mumetal cases, and each case is in turn mounted inside a rectangular ring of mumetal which lies in the same plane as the laminations. This ring is of approximately the same width as the overall width of the transformer. The arrangement is illustrated in Fig. 15.

(2.35) Radio-frequency interference.

Owing to the studios being in the same building as the ultra-short-wave transmitters at the station in question, the audio-frequency amplifiers were liable to be situated in a very strong radio-frequency field from both sound and vision transmitters. Whilst a very small pick-up from the sound transmitter would not be important, the nature of the modulation of the vision transmitter, together with its greater power, made it necessary to take every precautionary measure against interference.

In audio-frequency amplifiers there are so many components between valves, such as potentiometers and switches, which require to be brought away from the chassis on leads, that it is not easy to screen completely such amplifiers. This being the case, the method em-

ployed is to screen and filter the radio-frequency (r.f.) currents thoroughly only from parts of the circuit in which modulation might occur, i.e. from the valves. In this way no attempt is made to prevent r.f. currents from flowing in the transformers, potentiometers, wiring, etc., but these currents are very carefully filtered out before the valve is reached.

The amplifier chassis are made of copper, the valve-holders being mounted in the plane of the chassis. A typical valveholder assembly is illustrated in Fig. 16. A closely fitting copper screening box (A) covers the valve itself on the front of the chassis, while a similar but smaller box (B) covers the pins and leads at the back of the valve-holder. All leads passing through the screening boxes to join the valve to its external circuit are connected through screened filters* mounted in the bases of the screening boxes.

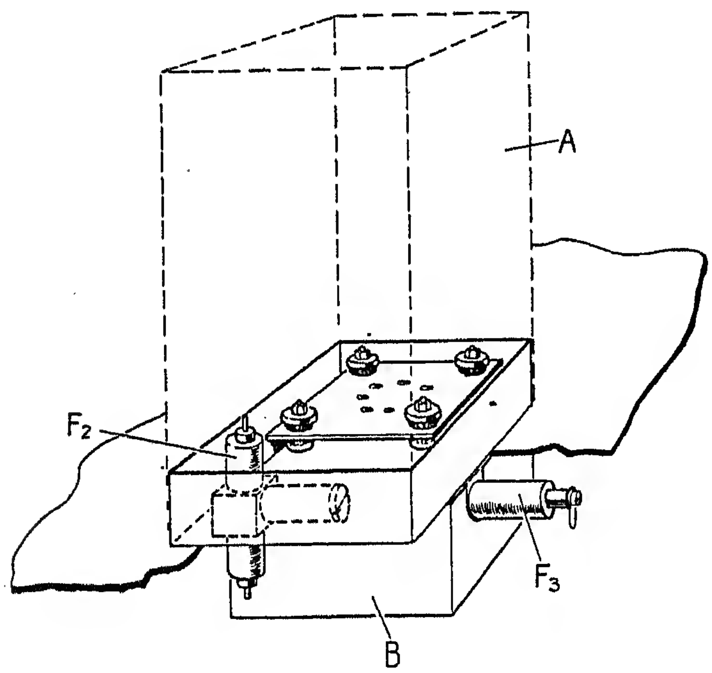

Fig. 16.—Sketch showing typical layout of screened valve-holder assembly for low-level stages.

A T-section radio-frequency filter (F_2) for the grid lead and a simple filter (F_3) for the anode are shown.

Several types of filters are used according to the circuit in question, but they are all mounted in cylindrical brass screens which pass through the valve screening boxes, as at F_2 and F_3 in Fig. 16. In the case of T section filters the brass tubes are screwed into a cubical junction block (J in Fig. 17) which is mounted on the chassis or screening box.

The filters are inserted in heater, cathode, grid, and anode leads of all early-stage valves. In the case of heater circuits the filters consist of a plain choke in each lead, with an external mica condenser at each end. For cathode circuits a similar choke is used except that its inductance, together with the distributed capacitance, forms an anti-resonant circuit at the frequency of the vision transmitter. As the cathodes are generally earthy for audio frequencies, condensers can be connected to earth at each end of the resonant choke. It is important that these condensers be connected directly from the filter terminal to the copper chassis with no intervening wire. The size of condenser used has a minimum impedance in the neighbourhood of the transmitter frequency. In some anode circuits a similar resonant choke is used, but the capacitance to earth is reduced to 50 $\mu\mu$F. For first-stage valves, however, such a capacitance would not provide sufficient r.f. attenuation. Moreover, even 50 $\mu\mu$F would be intolerable on any of the grid circuits. A third type of filter is therefore used. This is shown in Fig. 17 and consists of a section in which L_1 and L_2 are inductances resonated by their self-capacitance. The

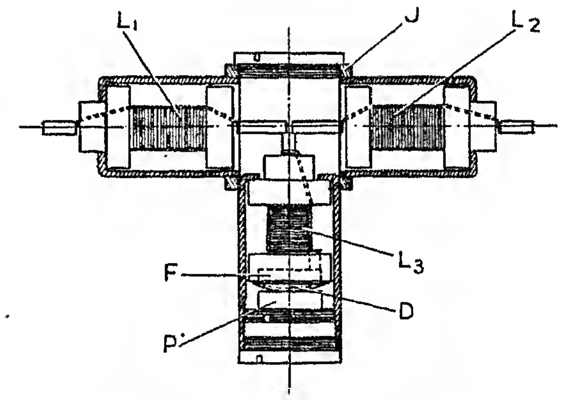

Fig. 17.—Cross-section view of T section radio-frequency filter.

inductance L_3 is tuned to the transmitter frequency by means of a small condenser consisting of the electrode (F) and the screw-in plunger (P), which flattens a dished metal disc (D), the latter being separated from (F) by a disc of mica. In this way very high attenuations, of the order of 80 db. or more, are possible with a total capacitance to earth of approximately 11 $\mu\mu$F.

The series grid resistances which are commonly used provide, together with the valve input capacitance, a further r.f. attenuation. This is the only filtering required in the case of valves carrying the higher audio-frequency levels.

Amplifiers built in this way have been tested in very high r.f. fields and with input circuits carrying r.f. currents, but no detectable interference has been produced.

(2.4) Control Circuits

Before describing the complete control arrangements it is thought desirable to explain a method of using a π

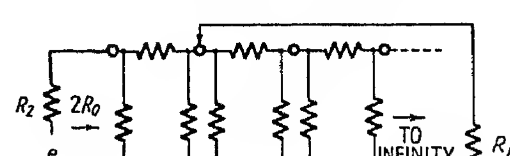

Fig. 18.—Basic method used for tapping π section attenuators.

section attenuator which forms an important part of these circuits and also of the testing equipment.

(2.41) Use of π section attenuators.

The attenuator in question* has the advantage of much simpler switching than the orthodox T or H types.

Fig. 18 shows a recurrent π structure consisting of an infinite number of sections of characteristic impedance $2R_0$ and attenuation per section α. At the sending end is a source, of impedance R_2; and tapped at any point down

* See British Patent No. 485618 (E. C. Cork and J. L. Pawsey).

* See British Patent No. 362472 (A. D. Blumlein).

the line is a load, of impedance R_1. Then it may be shown that the loss between source and load varies directly as the total attenuation of the included sections if

$$\frac{R_0(R_2 - 2R_0)}{(R_1 + R_0)(R_2 + 2R_0)}$$

is small compared with unity.

This can be made true in any one of the following ways:—

(i) $R_2 = 2R_0$, when R_1 may have any value.
(ii) R_1 very large, when R_2 may have any value.
(iii) Both (i) and (ii) are substantially true.

If the condition (i) holds, i.e. that the line is fed from a source whose impedance is equal to the characteristic impedance, then we have a network which has a loss between source and load equal to the nominal attenuation, no matter what is the impedance of the load; moreover, the impedance seen from the load is constant at R_0 since the impedance looking in either direction along the line is $2R_0$.

The same condition holds in the reciprocal case where R_1 is the source impedance and R_2 the load impedance. In practice, of course, the infinite line is replaced by one of a sufficient number of sections terminated by $2R_0$. A balanced network can be made in a similar manner, requiring only two switch contacts and four resistance elements per balanced section, the two adjacent shunt arms being commoned, as also are the final shunt arms and terminations.

(2.42) Fading and balancing circuits.

Reverting now to the control circuits,* these perform two broad functions. One is the selection, level adjustment, and combining of the channels required, and the other is the adjustment of the complete programme level to a value suitable for modulating the transmitter. These two functions, referred to as "fade and balance" and "main control" respectively, take place on one control desk in this equipment. This is a matter of convenience in this particular case: the main control could readily be put in a remote situation if desired.

The object of a fade-and-balance panel is to provide a fader which is used only as a fading switch, its purpose being to add or to remove a channel from the programme circuit in a gradual manner. It is always left in its maximum or minimum position and is never used for level-control purposes. The balance adjustment which follows this, enables the correct relative levels to be maintained between the several circuits to be combined. The balance of a multi-channel set-up is thus set according to previous experience or as established by rehearsal, each channel being faded-in as required. There are two fade-and-balance panels, each carrying four channels combined into a single output. Each of these combined circuits is connected to one of the two attenuators on the main control panel. Their outputs supply, through an optional combining circuit, either one or both of the main amplifiers.

The essential features of the control-desk circuits are shown in Fig. 19. On the left are eight input circuits, four on each fade-and-balance panel, which may be plugged to any of the twelve "A" amplifier outputs which terminate on a jack field on the desk. These input circuits are of 200 ohms impedance, with one side earthy. The faders F are simple universal shunts, of 10 000 ohms total impedance, connected across the balance attenuators B. The faders are tapped to give 1·5-db. loss per step for 17 steps, followed by 5 steps of 3 db. and a further 5 steps of 6 db., giving a total available fade of 70·5 db. The effect is that over the larger portion of the audible fading range the fading occurs uniformly in sufficiently fine steps to give an imperceptibly slow fade if required. If larger steps are used at the lower levels fewer contact studs are required, without introducing any audible steps in level. Such an arrangement is permissible, since with the separate balance-control facility the fader is always taken to its maximum position and all the 1·5-db. steps are always available for a fade-out. The balance attenuators, marked B, are π line networks of the type described earlier. They have a characteristic impedance of 400 ohms and consist of 29 steps of 1·5 db. each, giving a maximum balance control of 43·5 db. No "off" position is provided.

* See British Patent No. 486931 (H. A. M. Clark).

(2.43) Main control.

The main control attenuators are of the balanced form with a characteristic impedance of 400 ohms. These attenuators have 24 steps of 1·5 db. followed by 4 steps of 6 db. for a complete fade-out, i.e. a total range of 60 db. and an "off" position. The extreme right-hand end of these attenuators is terminated. The sliders are connected to the primaries of transformers T_1, while across the centre taps of these primaries is connected the primary of transformer T_2. These transformers feed the main or "B" amplifier input circuits, which are of an impedance very high compared with 200 ohms. A main amplifier can be connected to the secondary of any of the three transformers according to whether either or both channels are required.

(2.44) Combining circuits.

The balance attenuators are connected to the main control attenuators through centre-tapped auto-transformers L, each shunted by a resistance of 800 ohms. The function of these components will be better followed from Fig. 20, which shows the combination of two balance attenuators with one half of a main control.

It will be seen that the circuit can be considered to consist fundamentally of two sources, namely the balance attenuator outputs *ef* and *gh*, feeding a load *jk*, which is one half of the main control input, through the medium of a centre-tapped inductance L. It may be shown that if a resistance P be connected across L equal to four times the load resistance, the power from each of the two sources will divide equally between P and the load M, and that the impedance facing each source will be equal to twice that of the load M, irrespective of the impedance of the other source.

The half of the main control attenuator M under consideration will have a constant 200-ohm impedance at *jk*, facing the remainder of the circuit, since it is terminated at the right-hand end and the amplifier input impedance on the tapping *m* is substantially infinite. Hence the

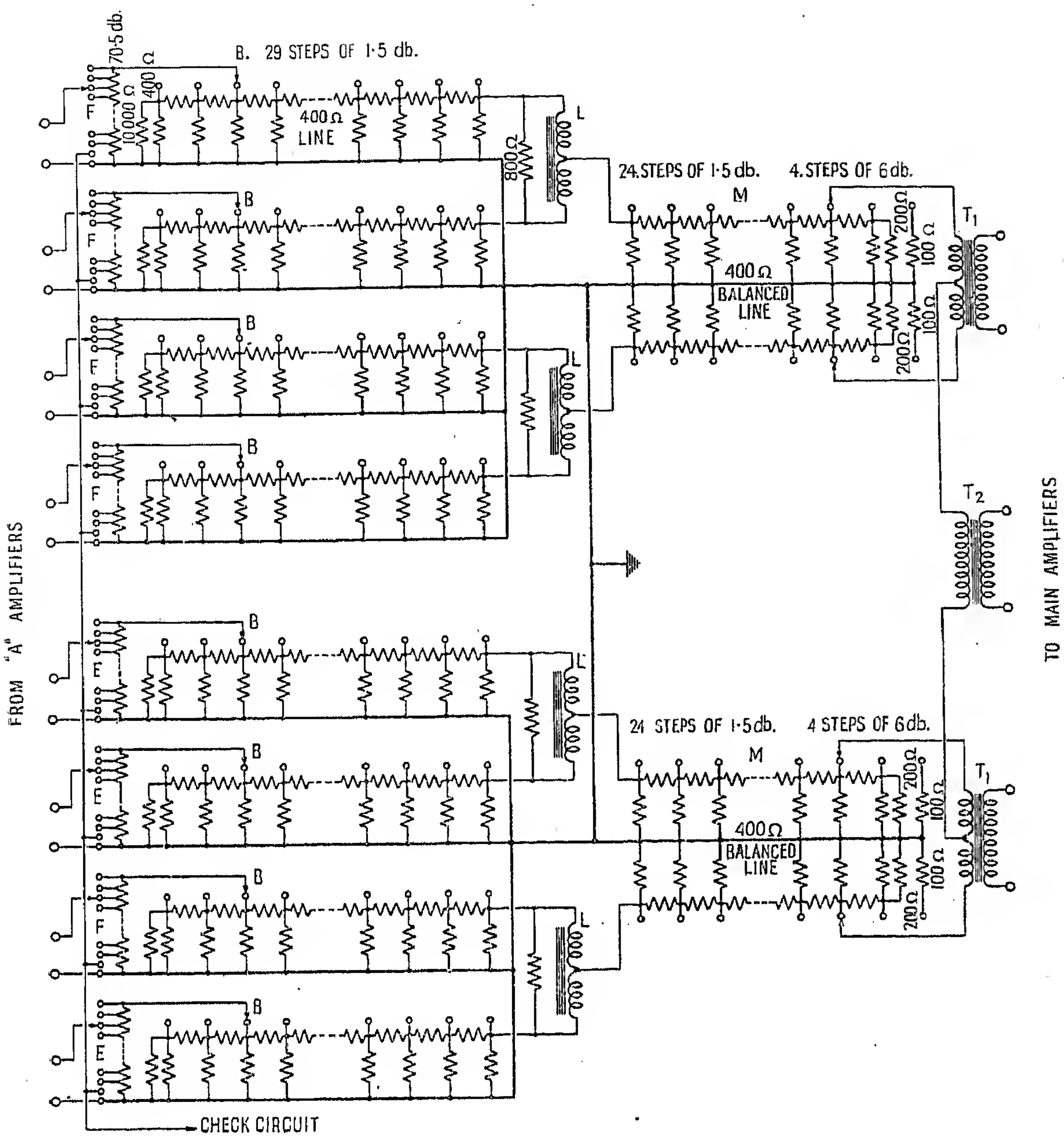

Fig. 19.—Control-desk circuits.

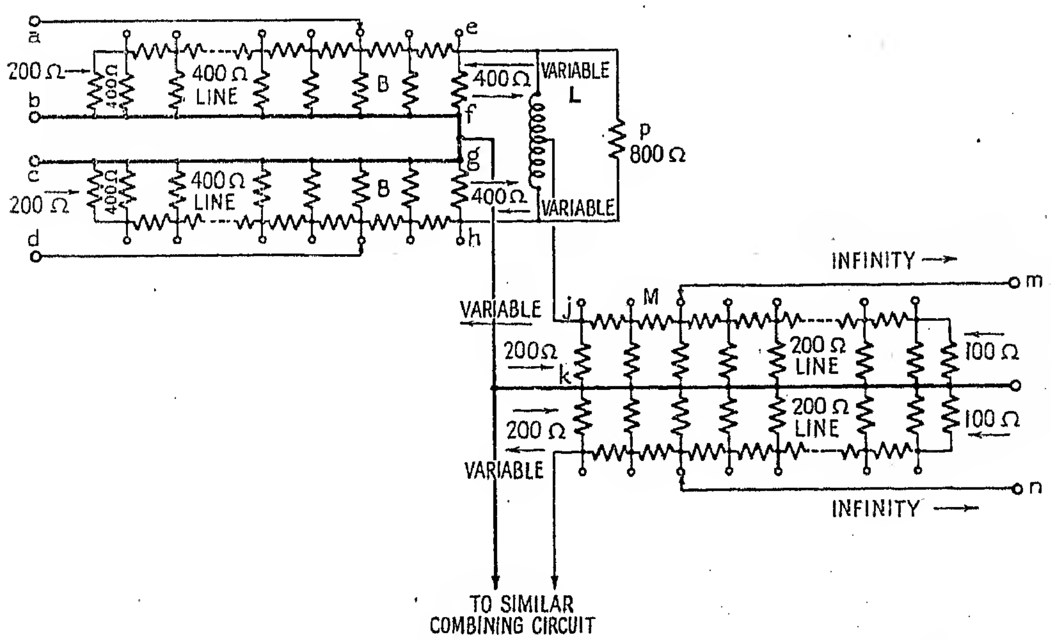

Fig. 20.—Basic mixing circuit.

resistance P is made equal to 800 ohms. The impedance facing each balance attenuator is therefore a constant value of 400 ohms, which provides them with good terminations. Thus the impedance seen at their inputs *ab* and *cd* is 200 ohms, which is the correct load for the "A" amplifier output circuits. The 10 000-ohm fader (not shown in Fig. 20) is in shunt across *ab*, but its effect is negligible.

The most important feature of the circuit, however, is that although the impedance of each of the sources referred to above, i.e. the impedance looking into the balance-attenuator outputs, is variable, owing to the 200-ohm "A" amplifier impedance being tapped across the attenuator the power supplied to the main control by the other balance circuit is unaffected.

It will be noticed that the impedance facing the main control input is variable, but, as has been previously pointed out, this is of no consequence, provided that the load across *mn* is of infinite impedance. The arrangement provides a means of combining the four channels of each fade-and-balance panel into a single channel, controlled by M in such a way that all four input impedances are 200 ohms exactly and the output impedance closely approximates 200 ohms, while the adjustment of balance loss, main control, or the fading-in of any circuit produces no change of loss whatever in any of the remaining circuits. This result is achieved with a standing loss of only 12 db. with all attenuators at minimum. Also the output impedance of any of the "A" amplifiers need not be accurately 200 ohms in order that the above conditions may hold.

A further feature of the fade-and-balance circuit is that the first stud beyond the "off" position of all the fader switches is not connected to the fader resistance but to a common circuit which, by the action of a key switch, may be connected to the monitoring telephones worn by the operator. In this way the latter may listen to a channel (at full "A" amplifier output level) before actually fading it into the programme channel. This is of convenience in ascertaining that the incoming channel is available and ready for transmission.

In order that the circuit may operate in the manner described over the whole frequency range, the auto-transformers L and the transformers T_1 and T_2 must have very small leakage inductance and a very high main inductance. The leakage ratio from primary to secondary for T_1 and T_2 is approximately 10 000 to 1, while in the case of the coupling between the two primary portions and the auto-transformer the leakage is only 1/100 000 of the main inductance. The latter result is achieved by the use of bifilar windings. In the case of T_1 and T_2, in order to provide a good impedance of 200 ohms at the secondary terminals the ratio is slightly modified to allow for the resistance of the windings.

The cross-talk between the two main outputs at the secondaries of transformers T_1 is 105 db., rising to 90 db. at 10 000 cycles per sec.

(2.45) Control desk.

The control desk has the two fade-and-balance panels on the left and the main control panel on the right. The latter contains the two programme monitoring meters, which will be described later. Between these panels is a jack field carrying all the "A" amplifier outputs, main amplifier inputs, the terminations of the inputs and outputs of the control sets, and any Post Office lines used for sending and receiving programmes outside the building. Supervisory lamps are fitted to indicate which channels are alive.

The operators' headphones can be connected to the monitor panel, the check radio receiver, or the check position on the fader, as described in Section (2.6).

(2.5) Output Distribution

An unusual feature of the equipment is the absence of trap-valves for the distribution of the audio-frequency output from the main amplifier to the transmitter and monitoring circuits.

The function of a panel known as the "output distributor" is, first, to divide the output from each of the main amplifiers in order to feed the loud-speaker amplifier input controls on the one hand, and the transmitter on the other, without cross-talk. This means that any load may be thrown into one channel without affecting the other. Secondly, the outputs intended for the transmitter from the two main amplifiers must be combined into a single channel to feed the transmitter input line.

The complete circuit of the output distributor is shown in Fig. 21, but the manner in which it is built up is more clearly understood from Fig. 22, which illustrates the basic principles. At A is shown a generator of impedance $2R$ and e.m.f. e. L is an ideal auto-transformer with an accurate centre tap. R,R, are two loads, and R/2 a balancing resistor, the whole forming a bridge circuit similar in principle to the "hybrid" coil of a telephone repeater. Each load R will receive one half of the power delivered from the source and will be fed from an impedance equal to R. There will be no power dissipated in R/2. If, however, the impedance of one load varies, the power passing to the other load will not be changed but the balance resistor R/2 will carry the surplus power. At B is shown a similar arrangement in which two generators of e.m.f.'s e_1 and e_2, each of impedance R, supply a load 2R through a centre-tapped auto-transformer and balance resistor R/2. One half of the total power from the two sources will be delivered to R/2 and the other half to 2R, the current to the load 2R due to one source being independent of the impedance of the other source. The arrangement is the same as that discussed in Section (2.44), but in this case the actual load is $2R$ and not $R/2$. At C is shown a combination of these two circuits. Each main amplifier forms the source of a circuit of the type shown at A. One output is the 200-ohm potentiometer which supplies the loud-speaker amplifier, while the other output forms one of the sources for a circuit similar to B. The combined output from the latter feeds the transmitter. If R is made equal to 200 ohms, then the impedance facing each amplifier and the transmitter will be 400 ohms, and the three balance resistances must be 100 ohms each. Thus any noises or loads thrown on to the loud-speaker amplifier circuits will not be communicated to the transmitter channel.

In the actual circuit (Fig. 21) the impedance required to load the main amplifier is 200 ohms; hence transformer T_1 is an auto-transformer with a $\sqrt{2}$ ratio and an accurate centre tap. The 200-ohm potentiometer of Fig. 22 is

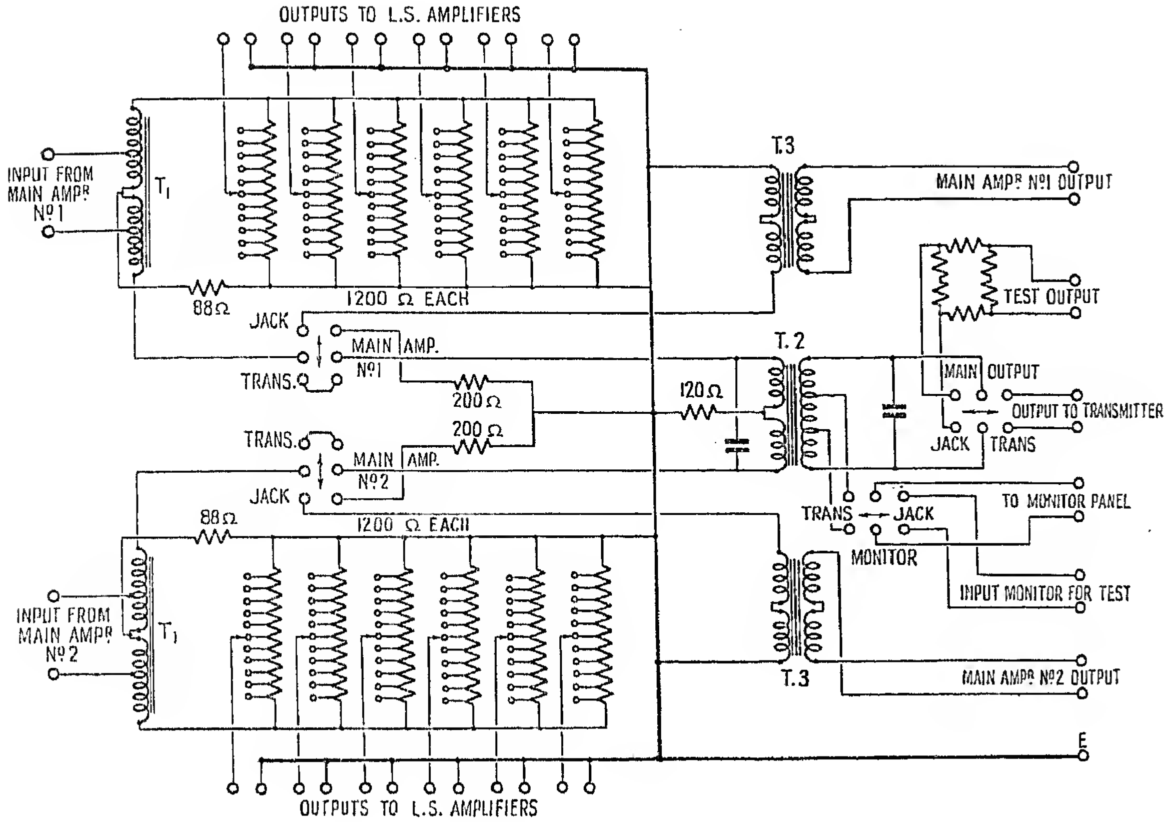

Fig. 21.—Complete circuit of output distributor.

made up of six 1 200-ohm potentiometers for controlling six loud-speaker amplifiers. The circuit on the other side of the centre tap of T_1 either feeds the transmitter through the combining transformer T_2 or its output can be switched to a jack through a unity-ratio transformer T_3 for use with the fold-back circuits. In the latter case a 200-ohm load is switched into the appropriate side of the combining transformer T_2 in order to maintain a correct impedance facing the transmitter. T_2 consists of a transformer of which the primary has an accurate centre-tap for combining purposes and the secondary raises the 400 ohms' output impedance to the 600 ohms which is required to match the transmitter feeding line. The secondary also carries two tapping points, giving an exact voltage ratio of $1/\sqrt{3}$ to the total secondary voltage. Across these are connected the open-circuit input terminals of the monitoring circuits. These are calibrated to indicate power levels by reading voltages across 200-ohm impedances. In this way the monitor reads correct power levels sent to the transmitter. The output of the main channel and the input to the monitor can be brought out to jacks for testing purposes.

It is by the use of this panel that the equipment can be divided into two separate channels, one of which can be used for transmission, while the other is used for any other purpose; or alternatively, the outputs of the two main amplifiers can be combined to feed the transmitter. The jacks connecting the loud-speaker amplifier inputs to the potentiometers feeding them are so arranged that any loud-speaker amplifier can be jacked to either main amplifier channel or bridged across both.

The balance resistors shown as being of 88 and 120 ohms respectively are not of the theoretical 100-ohm value owing to a correction for the resistance of the transformer windings. Similarly, the ratios of these transformers have to depart from the nominal value in order that the correct input and output impedance values may be maintained. Since these transformers operate at the highest level in the transmission channel, it is necessary to keep the bass loss very low to avoid harmonic distortion. This necessitates a type of winding giving a low leakage/inductance ratio. Even so, it has been found desirable to connect condensers across both windings of T_2. These condensers eliminate the effect of the

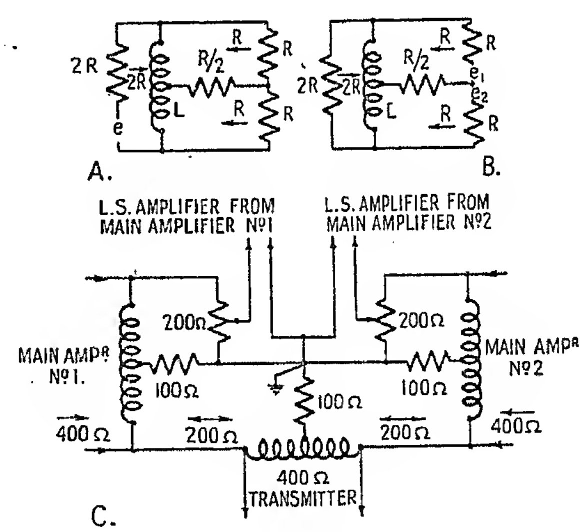

Fig. 22.—Basic circuit of output distribution networks.

leakage inductance of T_2 by forming a low-pass filter section with a cut-off at a super-audio frequency.

(2.6) Monitoring Circuits

The checking and monitoring arrangements comprise the following:—

(1) A meter reading the average level sent to the transmitter, in decibels, above 1 milliwatt. This meter is duplicated on the control desk and in the apparatus racks.

(2) A meter reading the peak modulation percentage, also duplicated on the control desk and apparatus racks.

(3) Check telephones. Four positions are provided, two in the control desk and two in the gramophone desk. These are normally fed from the audio input to the transmitter, but in the case of the control desk they can be switched to the output of a check radio receiver as mentioned in Section (1.5). A third position of the switch, which is fed from the check position on the faders, is also available at the mixer's position in the control desk.

(4) Five loud-speaker amplifiers, each capable of supplying two loud-speakers. The amplifiers can be fed from the audio input to the transmitter (via the output distributor panel) or from the check radio receiver.

The first three items above are provided by the monitor panel, which carries the monitoring telephone amplifier, the average programme-level meter, and the peak meter circuits.

All three of these circuits are fed via a common input valve. This valve works in a fully fed-back condition and has thus a gain of unity which is almost independent of the valve constants. Together with an input transformer of very low step-up ratio this stage constitutes a separator, in order that the metering circuits may be fed from a moderately low impedance and yet throw no load on the circuit across which the monitor panel is connected.

The monitoring-telephones amplifier consists of a single stage supplying four telephone outputs. A 4-way dividing circuit is used, similar in principle to that used in the output distributor, in order that the level to any one output may be unaffected by the load in any of the others. The input to this stage is controlled by a potentiometer.

(2.61) Programme-level meter.

The average-level meter circuit consists of a pentode amplifying stage with a small variable feedback for sensitivity adjustment, a diode rectifier, and a moving-coil meter circuit, the latter so arranged that the reading on the scale is proportional to the logarithm of the input direct current over a range of some 30 db. Actually two meters in series are used, one being on the panel on the apparatus bay, the other on the control desk.

(2.62) Peak-modulation meter.

The meter indicating peak modulation* consists of a full-wave diode peak voltmeter. The charging time-constant of the condenser through the valves is kept very small, while the discharging time-constant is of the order of 5 sec. The voltage across the condenser operates a cathode-follower† valve, which enables a robust meter of some 5 mA full-scale deflection to be used. The linearity and constancy of calibration are almost perfect when the valve is used in this manner. The standing current of this valve for no input is backed off. The sensitivity of the device is set by adjusting the cathode resistance so that the meter reads 100 % when the specified level of + 15 db. is sent to the transmitter. The gain of the audio stages in the transmitter is then adjusted to give the indicated depth of modulation at, say, 30 %, and a check made at 90 %.

The rapidity of indication of modulation peaks is limited only by the meter movement, but the long discharging time-constant keeps the meter at this point for a period long enough to give the operator time to observe the value of the peak. Any rapidly-following peak of still greater value will be indicated by the meter immediately, but lower peak-levels immediately following a high peak cannot be observed. The full-wave rectifier enables the peaks of asymmetrical waves to be observed.

The frequency characteristic of both metering circuits is shown in Fig. 23.

(2.63) Check radio receiver.

In order that the modulated r.f. ouput of the transmitter may be observed, a check receiver is provided. This consists of a diode rectifier fed through a tuned circuit directly from the transmitter output via an r.f. line coupled to the main feeder. Some 4 watts of r.f. power are passed into the terminating resistance of the line in the receiver. A rejector circuit tuned to the vision-transmitter frequency is connected between the line termination and a tuned circuit which is tuned to the sound-transmitter frequency. The audio output across the diode load feeds two amplifiers, one of which is identical

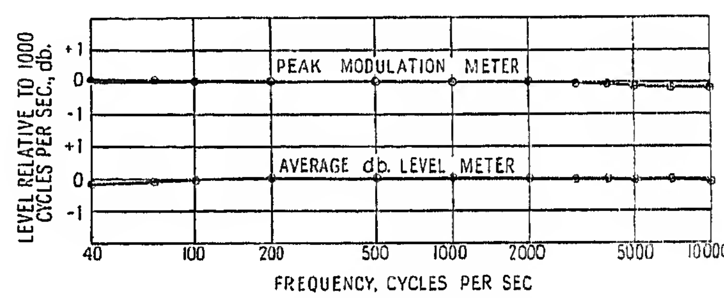

Fig. 23.—Frequency characteristics of programme-level meter and peak modulation-level meter.

with the monitoring-telephone amplifier described above, while the other is a push-pull stage which feeds four potentiometers of the same type as those on the output distributor. The loud-speaker amplifiers, described below, can be plugged at will either to the output-distributor potentiometers or to those on the check receiver. The levels are so arranged that the same loud-speaker level results for the same potentiometer setting at both output distributor and check receiver.

(2.64) Loud-speaker monitoring.

The loud-speaker amplifiers are required to raise the level from the potentiometers of the output distributor or check receiver to loud-speaker level. The input transformer is of low ratio and is suitable for working from a widely varying impedance, such as is seen looking into the potentiometers, with no appreciable change in characteristic. A low-gain first stage feeds a push-pull output stage of conventional design.

For the operation of a large loud-speaker in the studio, a similar amplifier is provided with an output stage consisting of 2 D.A.60 valves in push-pull. An audio-frequency output of 40 watts is available.

The loud-speakers all employ moulded paper diaphragms, reinforced with aluminium centres and suspended at the periphery by very flexible leather. The diaphragm is in the form of a cone, the cross-section of

* See British Patent No. 477392.
† C. O. Browne: *Journal I.E.E.*, 1938 vol. 83, p. 779.

which varies from circular at the centre to an ellipse, with axes of $11\frac{3}{4}$ in. and 6 in., at the outside edge.* This shape of diaphragm has two distinct advantages over the usual circular type. First, resonances in the region from 1 000 to 3 000 cycles per sec. are smoothed out; and secondly, the distribution of high-frequency radiation in the plane containing the major axis is considerably improved. The high frequencies are radiated by the aluminium centre portion of the diaphragm, which is effectively damped by the paper outer diaphragm, which in its turn is terminated by the damping of the leather surround.

For checking sound quality, and for balancing purposes, the units are mounted in 4-ft. square baffles. In these circumstances the axial response characteristic from 500 to 8 000 cycles per sec. does not depart from the mean by more than $\pm$ 5 db. Below 500 cycles per sec. the response is determined by the baffle, and falls by 10 db. at 50 cycles per sec.

Where loud-speakers are required for cueing purposes only, and space is restricted, a small cabinet is employed of a type which, while causing bass attenuation, avoids resonance.

For reproduction of sound in the studio a bank of four loud-speaker units is assembled on a baffle approximately 4 ft. square. Two loud-speakers are mounted so that their diaphragms lie in the main plane of the baffle and the other two are mounted on side panels which are inclined at 20° on either side of the main baffle.

(2.7) Talk-back System

In a television station a number of talk-back facilities are desirable.

The producer must be able to speak to any of the cameramen or to the film operators. This facility is provided by means of various microphones—located on the producer's desk and near the vision monitors, etc.—the output from which, after suitable amplification, supplies a distribution network. This comprises a number of keys for switching any required camera headphone set on to the talk-back circuit. A further key closes all camera headphone circuits simultaneously. In addition, the studio loud-speaker can be connected to the talk-back circuit to allow speaking to artists in the studio. Further, in the case of outdoor broadcasts a loud-speaker can be connected to the camera talk-back circuit, which is then fed at loud-speaker level. By this means the producer can direct artists and cameramen at rehearsal. The latter wear headphones during an actual transmission.

To facilitate these requirements the output stage of the talk-back amplifier is provided with a dividing circuit similar to that shown at A in Fig. 22, but in which the auto-transformer is so tapped that the two output channels differ in level by 20 db.

(2.8) Power Supply

The whole of the equipment is operated from a 50-cycle 240-volt single-phase supply, no batteries of any kind being employed. The use of large units capable of supplying a number of amplifiers has been preferred to the use of individual supply units, as being more efficient and facilitating simple stand-by arrangements.

As there are a large number of amplifiers, etc., only some of which are required for use at any one time, the supplies to each amplifier are individually switched in order to conserve power and valve life. Both heater and H.T. supplies must therefore be of good regulation.

Moreover, owing to the very low low-frequency cut-off of the amplifiers, considerable trouble is met if the H.T. supply has any very low-frequency fluctuations upon it. Even with the considerable amount of smoothing employed it is impossible to filter out fluctuations below about 5 cycles per sec. which are due to rapid changes in line voltage of the 50-cycle supply. It has been necessary, therefore, to stabilize the anode supplies individually for all the "A" amplifiers. Triode stabilizers are used,* a single valve being provided for each stabilized output. Individual stabilizers are provided for each amplifier in order to permit circuits to be switched while other amplifiers, supplied by the same rectifier, are in use for transmission. All the anode circuits are supplied from two mercury-vapour full-wave rectifiers.

The heaters of all microphone and main amplifiers are fed directly from a single 50-cycle 13-volt transformer with the centre-point earthed. The loud-speaker amplifiers, which incorporate directly-heated 4-volt valves in the output stage, are fed from a separate transformer with a winding for each amplifier.

(3) PERFORMANCE

(3.1) Levels and Ratings

Before describing the performance of the complete station, it may be advisable to discuss briefly the methods adopted for rating amplifier gain and microphone response.

(3.11) Amplifier gain.

The gain of an amplifier is defined as the difference between the power level in the output circuit and the power level in the input circuit. By "power level" is meant here the maximum power level available from the circuit, i.e. supplied into a matched load. If matched conditions do not apply at the input or output of any particular amplifier, the change in voltage level thus caused is included in the amplifier gain figure.

For example, most of the amplifiers operate from and into a 200-ohm circuit. The output impedance of the amplifier may be 200 ohms, and the output level is based on the power delivered into a 200-ohm load. The input impedance, however, may be very high compared with 200 ohms, and hence the actual input power is negligible. The input power level is based on the power which the 200-ohm sending impedance would deliver to a 200-ohm resistance. Actually, the input voltage level to the amplifier will be 6 db. higher than the voltage level across the sending circuit would have been across a matched impedance. This 6 db. thus becomes expressed as part of the amplifier gain.

The electrical zero level is 1 milliwatt. Voltage and current levels are expressed against a zero level of 0·4472 volt (r.m.s.) and 2·236 mA (r.m.s.), i.e. the voltage and current obtained in a 200-ohm circuit at 1 milliwatt.

* British Patent No. 442165 (G. F. Dutton).

* See C. O. Browne: *Journal I.E.E.*, 1938, vol. 83, p. 780.

(3.12) Microphone response.

The zero acoustic-power level is taken as $(1 \text{ dyne per cm}^2)^2_{mean}$. Thus acoustic-pressure levels can be obtained, like voltage levels, from $20 \log_{10} p$, where p is the r.m.s. pressure in dynes per cm^2.

The response of a microphone can then be defined as the electrical output level minus the acoustic input level. This is a much more satisfactory rating in practice than that based on using an open-circuit e.m.f. of 1 volt as a zero, since the microphone response can be added directly to amplifier gains, attenuator losses, etc., when discussing the levels in a complete equipment.

A single exception arises in the case of the moving-coil microphone described in Section (2.11) of this paper. It is essential that an equalizer of widely varying impedance should immediately follow such a microphone. In this case it is the custom to rate the microphone response in terms of the open-circuit voltage level (zero being 0·4472 volt), and the microphone amplifier gain as the output power level minus the open-circuit e.m.f. level of an input circuit which has an impedance equal to the static impedance of the microphone. These two responses are taken at 500 cycles per sec. and when added together give the overall microphone and microphone-amplifier response in the same terms as for any other microphone, i.e. acoustic level to electrical power level. Since the microphone can only be worked directly into this particular amplifier, this exceptional case raises no difficulties.

(3.13) Other input sources.

All other devices such as gramophones and film sound-heads are rated in a similar manner. The zero level for gramophone discs is based on $(1 \text{ cm. per sec.})^2_{mean}$, whilst a constant-amplitude system such as variable-width film recording can be based upon $(1 \text{ cm.})^2_{mean}$ as a zero power level.

(3.14) Power levels throughout the system.

Fig. 24 shows the levels operative throughout the system. The conditions are set for a normally-encountered instantaneous peak level to modulate the transmitter to 100 %. Input conditions are shown for gramophone, and for ribbon and moving-coil microphone, operating at average peak speech-levels.

The first fall in level is produced by the conversion in each case to electrical outputs. The apparently low output of the gramophone pick-up circuit is partly due to equalization for bass restoration at this point, but a fixed loss is also inserted to enable a standard type of amplifier to be used. It will be noted that the electrical output of the ribbon microphone at — 72 db. is the lowest level in the system, since no form of mixing is employed until after the microphone amplifiers.

The next level change is a rise to approximately zero level. This is occasioned by the " A " amplifiers, the gain of which is such as to produce this output level with average conditions. It will be appreciated that the actual output level will be fluctuating considerably about (chiefly below) zero level, and Fig. 24 only shows the ideal peak conditions. The *average* level would be between — 10 and — 20 db. If the level were to be consistently lower than this, owing to the transmission of a programme consisting of abnormally low sound levels, the gain of the " A " amplifier could be raised by 10 or 20 db. by means of the preset gain controls before the beginning of the transmission.

The attainment of a normal peak level of about 0 db. before fading and mixing ensures that the level at all the control attenuators is high enough to render noise or cross-talk unlikely. This also enables maintenance work on the switches to be reduced.

The losses of the control desk can now be considered. A balance-attenuator loss of 21 db. is shown in Fig. 24 as representing an average value. The standing loss of

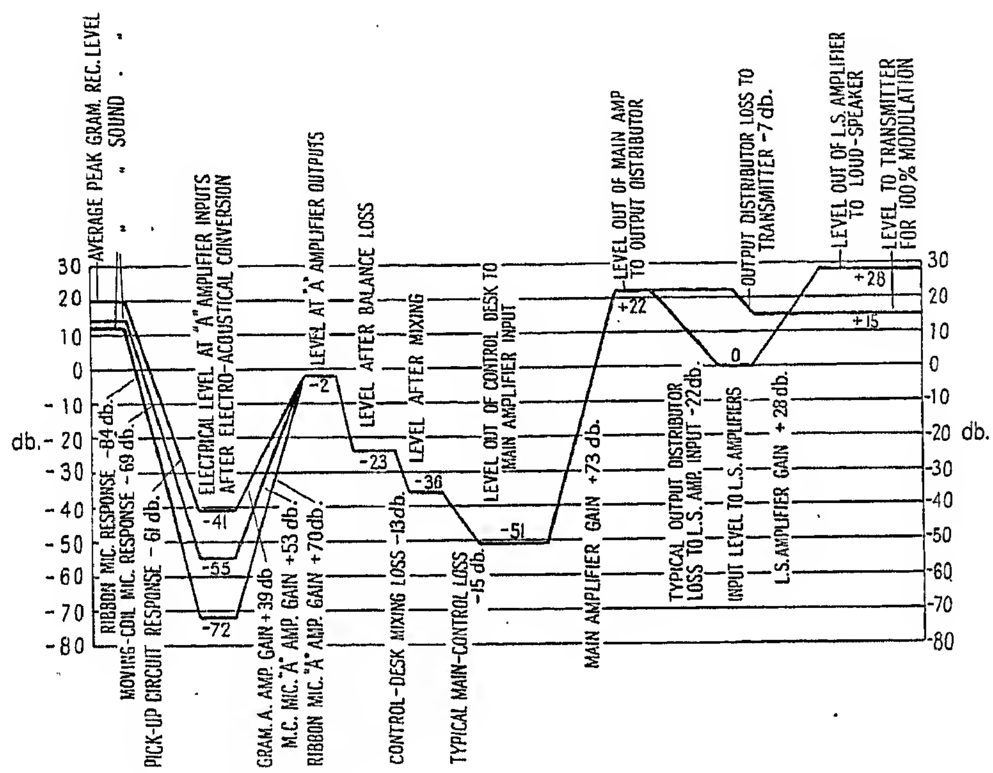

Fig. 24.—Level diagram of complete system. Instantaneous peak levels are shown throughout the system to produce full modulation.

the control desk due to the mixing circuits is 13 db. with all controls at maximum. This is 1 db. greater than the value given in Section (2.44), owing to the resistance losses of the transformers. An average value of 15 db. in the main control brings the level down to − 51 db.

The main amplifier follows the control desk with a gain of 73 db., bringing the level to the output distributor up to + 22 db. There is a nominal loss of 6 db. (actually 7 db., including transformer losses) to the transmitter input at + 15 db. This last circuit is of 600 ohms impedance, a level of 15 db. above 1 milliwatt, corresponding to a voltage of 4·35 volts. This is the input voltage for which the transmitter is adjusted to give full modulation.

Fig. 24 also shows the output-distributor potentiometer loss; the loud-speaker amplifier gain raises the level to + 28 db.. This is sufficient for an average listening level with the loud-speakers supplied.

attenuator to be measured. The attenuator consists of 10 sections of 1 db., 5 sections of 10 db., and an optional 50-db. fixed attenuator, all of 400 ohms impedance, giving a maximum loss of 110 db.

The open-circuit voltage level across the output contacts is equal to the current level supplied to the attenuator minus the attenuation of the sections included between the input and output terminals. When the sliders are set for zero attenuation, the input and output terminals are connected together and across them there are left two series of terminated sections which together are equivalent to a plain 200-ohm resistance. If now the attenuator feeds a load of 200 ohms, then the source has to supply current into both the 200-ohm shunt (i.e. the attenuator at zero loss) and the 200-ohm load. Thus if a current of + 6 db. is sent into the attenuator, the level supplied into the load will be equal to zero level minus the attenuation inserted.

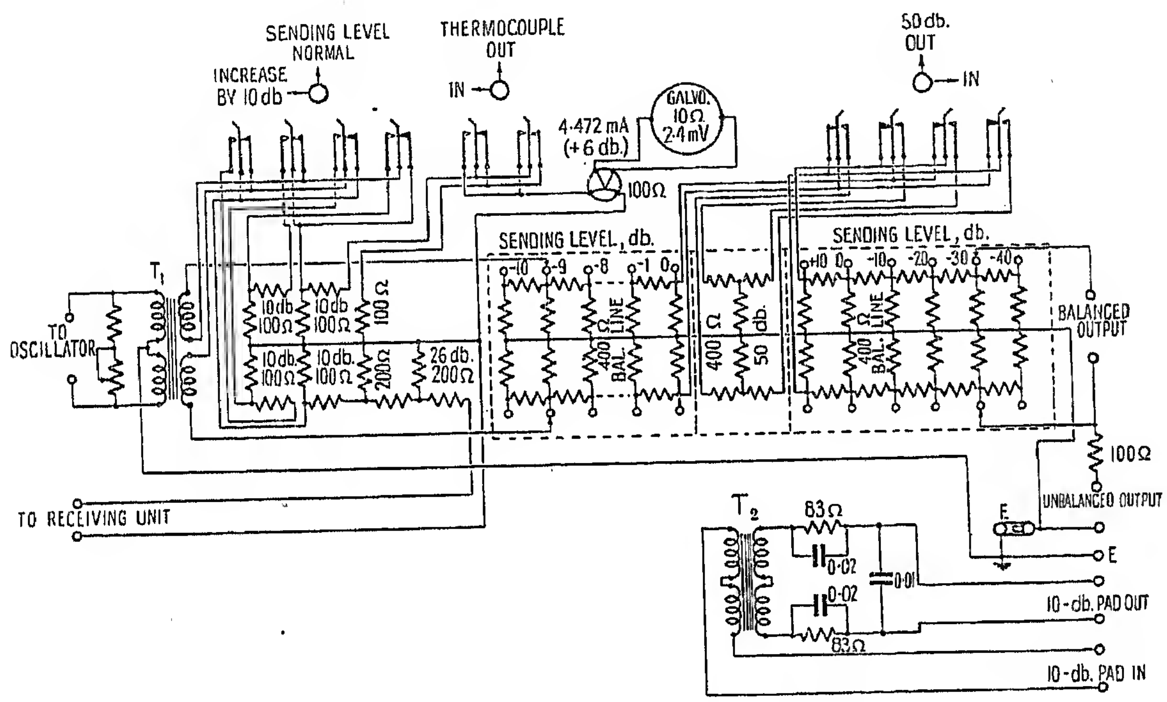

Fig. 25.—Sending unit of gain-measuring set.

(3.2) Testing Equipment

A gain-measuring set suitable for measuring the gain of any part of the equipment is contained in one of the bays.

(3.21) General principles of the gain set.

Although the basic principle employed is well known, it is thought that certain details of design will be of interest. The attenuators employed consist of two π networks of the type referred to in Section (2.41), where the output is taken through a tapping switch, the studs of which are connected to the junctions of the π sections. When such an attenuator is fed with a constant current representing an infinite sending impedance, the open-circuit voltages across the tappings will be reduced according to the loss in each section of the line, and the effective impedance facing the load will be invariant.

(3.22) Sending unit.

The sending unit, of which the circuit is given in Fig. 25, consists essentially of an attenuator with calibrating circuits which enable the current fed into the

The current actually supplied to the attenuator is normally calibrated to a level of + 16 db. Thus the maximum output level from the gain set is + 10 db. and the minimum − 100 db. For sending accurately-known levels the current is set, by means of a thermocouple and suitable attenuating pads, either to the normal value, or 10 db. higher in order to obtain an output level of + 20 db. when desired. For general gain-measurement the thermocouple is removed from circuit and the current is calibrated by means of the receiving unit, which can be connected across the attenuating pads referred to above (see Section 3.23). The current supplied to the sending unit from the oscillator is conveniently adjusted by means of a variable shunt across the primary of the supply transformer, since the oscillator supplied with this equipment has a pentode output stage.

An unbalanced 200-ohm sending circuit is obtained by connecting a 100-ohm resistor in series with one half only of the main attenuator. In this case the e.m.f. delivered from the line is 6 db. lower than when working in the balanced condition. This is a correction for which allowance must be made.

When testing some apparatus it may not be desirable to make a direct connection to its input terminals, in which case a transformer network is employed between the sending unit and the input terminals of the apparatus under test. This circuit is contained in the sending unit, and consists of the transformer T_2 (Fig. 25).

It is obvious that any transformer other than an ideal transformer would introduce a loss which would be variable with frequency. To overcome this, the transformer circuit is made to have a constant 10-db. loss. This is done by using a transformer with a step-down ratio of $1 : \sqrt{10}$ and with a very large number of turns, thus ensuring that the low-frequency loss is extremely small. There will, however, be considerable leakage inductance and series resistance. The resistance seen at the secondary terminals when the primary is connected to the 200-ohm gain set will be 20 ohms plus the total transformer resistance referred to the secondary. By Thévénin's theorem, the circuit will produce a constant 10-db. loss if its open-circuit voltage is reduced by $\sqrt{10}$ and its impedance remains invariant at 200 ohms. Thus it remains only to build-out the secondary impedance to a constant value of 200 ohms. The condensers and resistances in the secondary circuit are so proportioned to the leakage inductance that the impedance remains substantially constant and resistive over the required frequency range.

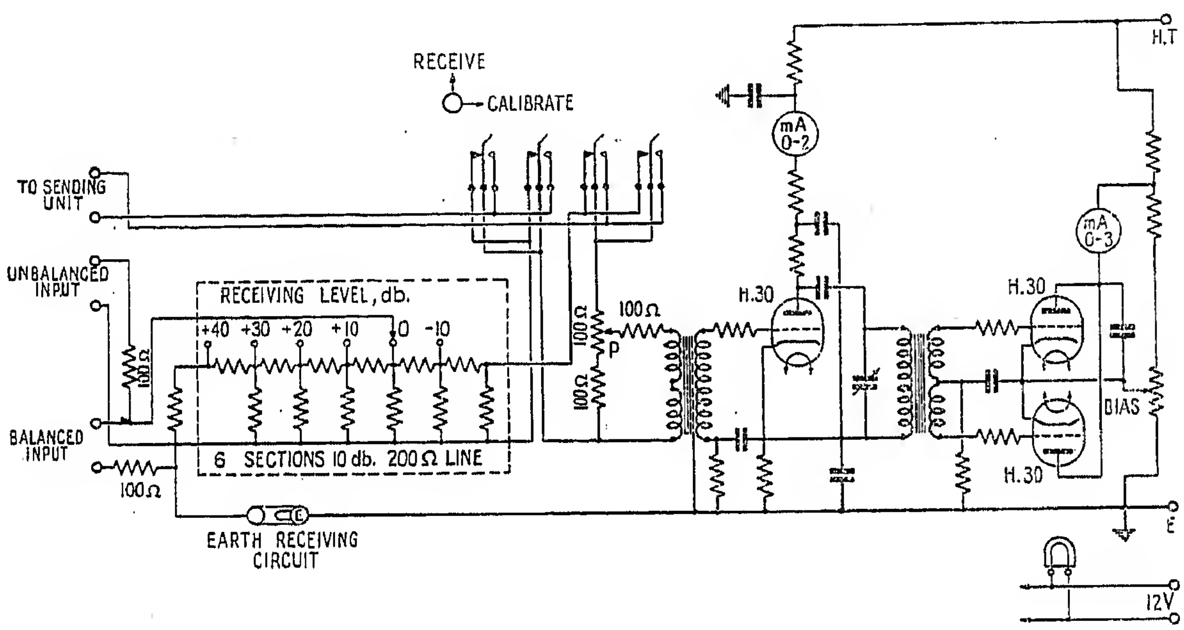

Fig. 26.—Receiving unit of gain-measuring set.

(3.23) Receiving unit.

The receiving unit (Fig. 26) consists of an amplifier-detector unit with an adjustable input attenuator designed to accept input levels, either balanced or unbalanced, from -10 db. to $+40$ db. By throwing a key the input to the amplifier-detector can be connected to the sending unit for calibrating purposes.

The amplifier is an H.30 valve working as a simple triode and feeding a pair of H.30's which operate as anode-bend rectifiers with their grids connected in push-pull. The object of using a push-pull detector is to obviate the presence of "turn-over" effects. This means that the true r.m.s. reading of the testing wave-form is obtained irrespective of any poling in the amplifier under test. The anode-circuit meter is scaled for fractions of a decibel above and below zero level.

The characteristic of the receiving unit is flat to within $\pm 0 \cdot 2$ db. from 40 to 10 000 cycles per sec. Since the same unit is used for calibrating the sending current this introduces no error in the measurement of the gain characteristic of an amplifier, but represents a slight change of testing level with frequency.

The oscillator is a straightforward beat-frequency type, calibrated from 40 to 10 000 cycles per sec. Its frequency is set by means of a self-contained 250-cycle tuning fork. The operation of a "check frequency" switch mechanically strikes the fork and throws a pick-up coil into the detector circuit. A trimming condenser is then adjusted on the variable-frequency oscillator until no beats are indicated on the anode-current meter with the oscillator dial set to 250 cycles per sec.

Beneath the gain set is a jack panel connected to a number of lines (shown dotted in Fig. 1) which go to convenient positions whence they can be jumpered to the input and output of any unit in the system. In this way any unit, or combination of units up to the complete channel, can be measured without the use of trailing temporary leads. The input and output leads are carefully segregated and run by different routes to avoid any errors due to cross-talk.

(3.3) Overall Performance of System

The frequency characteristic of the complete system was measured after installation. In this case the set-up consisted of a ribbon microphone "A" amplifier, a fade-and-balance panel and main control, a main amplifier, and an output distributor to the 600-ohm transmitter feed line. The gain was constant with frequency to within $\pm 0 \cdot 1$ db. over the specified range of 40 to 10 000 cycles per sec. Above 10 000 cycles per sec. the overall gain rises slightly, being about 1 db. up at 20 000 cycles per sec. Almost identical characteristics are also obtained through any of the film sound, or gramophone channels.

Tests were made to measure the overall harmonic level. It will be appreciated that where several amplifiers, all producing similar distortion, are connected in cascade, it is possible to balance out to a certain extent some of the enen harmonics by using a particular poling of the convections between the output of one amplifier and the input of the next. In order to avoid prejudicing the results in this manner, the input connections of the main amplifier were poled for the test in the direction which gave maximum harmonic output.

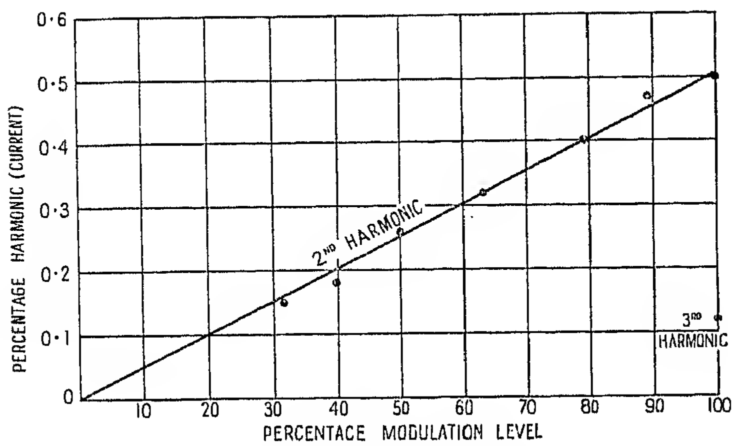

Fig. 27.—Overall harmonic distortion of complete programme channel for various levels at 1 000 cycles per second.

Fig. 27 shows the harmonic level plotted against output in terms of a sine-wave output voltage sufficient to give full modulation to the transmitter. The curve is for the 2nd harmonic, and a single point is shown for the 3rd harmonic, difficulty of measurement precluding any points below 0·1 %. This test was made at 1 000 cycles per sec. A test under the same conditions at 40 cycles per sec. gave a result of 0·45 % 2nd harmonic and 0·66 % 3rd harmonic at 100 % modulation level. The latter figure substantially indicates the value of the distortion introduced by all the iron circuits in the system, since at 1 000 cycles per sec. the 3rd harmonic is negligible. It should be noted that a total of seven transformers and chokes with iron cores are included in the main programme channel. Moreover, there is no possibility of 3rd-harmonic mutual cancellation. Intermodulation figures are not given as an indication of distortion, as an accurate method of measurement was not available for the low values obtaining.

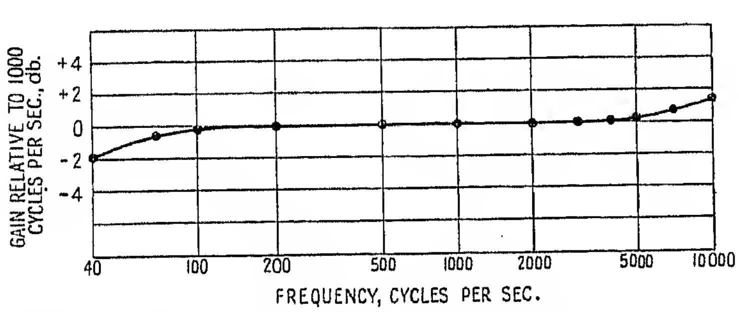

Fig. 28.—Overall frequency response to modulated radio-frequency output of transmitter.

The system was designed to operate into a radio transmitter designed and constructed by Marconi's Wireless Telegraph Co., Ltd. Although this paper is not concerned with the performance of the radio transmitter some figures on the overall performance of the complete sound equipment, from microphone amplifier input to modulated r.f. output, may be of interest. Fig. 28 shows the overall frequency characteristic. An overall measurement at 1 000 cycles per sec. at 90 % modulation gave 2 % 2nd harmonic.

(3.4) Conclusions

The paper describes the design and construction of an equipment with a performance which is probably better than that obtained in common use at many high-grade broadcasting stations. Advantage can be taken of such equipment in conjunction with an ultra-high-frequency transmitter such as that generally used at television stations.

As a result of the experience gained in the design and use of the equipment a number of features have come to light. That the sound quality transmitted by the equipment can be satisfying and pleasing there has been abundant evidence. In the authors' opinion, the low odd-harmonic distortion (and intermodulation) level at the low-frequency end of the scale is probably even more important than the extension of the frequency range in the upward direction.

It can also be stated that the requirement of a very low distortion level at low frequencies was undoubtedly the most difficult part of the specification to meet.

It is clear that complete mains operation, including the use of a.c. heating, is perfectly feasible even for first-stage amplifiers following insensitive types of microphone.

The cut-off at each end of the frequency range has purposely been made gradual rather than sharp, and this has led to a number of practical difficulties. Considering first the low-frequency end, the most marked of these has been the question of fluctuation of H.T. supply voltage. Without the use of the stabilizing circuits referred to in Section (2.8) of the paper it is doubtful whether it would have been possible to maintain the overall gain so level at the extremely low frequencies.

Interfering noises such as studio rumbles and microphone boom noises are much more prevalent with an extended low-frequency range, and it remains to be seen whether the practical limitation has been reached.

At the high-frequency end of the spectrum it cannot be denied that background hiss becomes more marked with the extension of the range; a large part of this arises from acoustic sources. That the practical limit has been already exceeded in this direction in connection with recorded sound is well known.

After being in service for a period of 2 years, the equipment appears to have fulfilled the desiderata, somewhat uncertain at the outset, for a single-studio television station. All the facilities included have been of value at some time or other, whilst if there was any error in the original specification it appears to have been more in the nature of an under-estimation of the number of channels required, than the reverse.

(4) ACKNOWLEDGMENTS

The authors' grateful acknowledgments are due to Electric and Musical Industries, Ltd., in whose service the work was undertaken; to Mr. I. Shoenberg, the Director

of Research, for permission to publish the information; and also to Mr. G. E. Condliffe. Special acknowledgment must be made to Mr. A. D. Blumlein, who was responsible for many of the ideas embodied in the apparatus, and without whose original work the paper could not have been written. Acknowledgment is also due to Dr. G. F. Dutton for the design of, and information concerning, the loud-speakers described in the paper. The value of the work of all the engineers who assisted in the construction, testing, and installation of the equipment is no less appreciated.

The authors wish to thank also the British Broadcasting Corporation, and Marconi's Wireless Telegraph Co., Ltd., for permission to publish certain measurements made on the system after it had been installed at the London Television Station.

DISCUSSION BEFORE THE WIRELESS SECTION, 3RD MAY, 1939

Mr. H. L. Kirke: The authors state that when they were asked to design the audio-frequency equipment described in the paper, very little was known as to what was required in the way of flexibility, but they realized that they would have to cater for a very flexible system. They produced a system which we who are engaged in ordinary sound broadcasting would very much like to use, but which we have been unable to adopt on account of cost and complication in a large number of cases.

The excellent performance of the apparatus from the point of view of quality, as regards both frequency-characteristic and amplitude distortion, is worthy of comment, but although the apparatus was designed several years ago its performance is in keeping with that of high-quality modern speech apparatus. The quality of the sound received from Alexandra Palace is good on a large number of occasions (it cannot be perfect on some occasions because of the necessity for rather unusual microphone placing). Comparing it with the transmission of sound on the ordinary programmes on medium waves, one finds that on medium-wave transmissions the things which annoy one are the interference and the fact that the frequency range has to be limited at the receiver.

The mixing circuits used by the authors are interesting, as they do their work without the use of special trap valve amplifiers for isolating one circuit from another. The loss in such circuits is rather high, but in these days when it is very easy and relatively cheap to use high-gain amplifiers perhaps that is unimportant.

As regards the authors' remarks on terminal impedances, there seems to be a general tendency to reduce such impedances to about 200 ohms, although for most of the circuits used in broadcasting the B.B.C. employs 600 ohms. It is interesting to note that even in ordinary telephone line work, at any rate for broadcasting, the impedance value of the line is very seldom 600 ohms; in fact, the value often drops to 100–200 ohms and lower, and usually varies considerably with frequency.

Since the equipment was put in at the Alexandra Palace, the system of programme metering has been modified to keep in line with modern B.B.C. and European standards. The present instrument responds to the quasi-peak valve, the incremental time being about 10 millisec., and the decremental time 1–2 sec.

Mr. W. West: I wish to draw attention to the position occupied in the paper by monitoring loud-speakers. Although these are not in the circuit of direct transmission, they can nevertheless affect the quality of the transmission. Mention is made of two different types of microphone, having different polar characteristics; and the technique of selection, placing, and orientation of microphones is, I presume, based on judgments of the quality of the transmission as heard from a monitoring loud-speaker. Such judgments may even have a wider influence, for example, on the acoustical design of studios, and the loud-speakers hold a more responsible position than that usually associated with monitoring equipment. This consideration is emphasized by the fact that the performance of the loud-speakers is poor by comparison with the extremely high standard set by the rest of the equipment described in the paper. One reason why the performance of loud-speakers, generally, remains relatively inferior is, I think, the absence of a suitable and widely recognized criterion which takes account of the type of room or auditorium in which the loud-speaker is to be used. The performance of the loud-speaker described in the paper is quoted in terms of departures from uniformity of the frequency characteristic of sound pressures in free space, at a point on the axis of the diaphragm. This criterion is only suitable when the loud-speaker is heard at a position near the axis in the open air, or in a room which is very heavily damped for all audible frequencies.

The use of the term " telephone " to refer to a " telephone receiver " (see B.S.I. Glossary No. 661, Item 4209) can lead to confusion with the popular meaning of the word, and is to be deprecated.

Mr. C. H. Colborn: In considering this paper I think we might first deal with those features of the equipment which are specially relevant to television. The two principal features are: (1) the means adopted to prevent ultra-short-wave interference, which appear to be very satisfactory; and (2) the provision of what are known as fade-and-balance controls.

The fade-and-balance control is used only in sound equipment for television. While it can be argued that the presetting of the balance is a desirable feature having regard to the speed at which the operator has to move from one source to another, from the designer's point of view it has to be borne in mind that in a large studio with many sources a very large and expensive mixing panel becomes necessary.

I gather that the authors were forced to adopt high-level mixing because they were using two different types of microphone, one of which involved a very complex equalizing circuit which can most conveniently be fitted in an amplifier. Broadcasting engineers are continually faced with this problem of high-level mixing versus low-level mixing. At Alexandra Palace, 12 amplifiers have to be provided in order to deal with the microphone, gramophone, and film channels, and in large premises the cost of providing amplifiers to give high-level mixing will clearly be considerable. The authors will no doubt say that with low-level mixing, apart from possible noise

troubles they cannot get circuits in which one source is unaffected by the others. That unfortunately is so at the moment, but it is to be hoped that ultimately a more sensitive microphone may be forthcoming which will make it possible to tolerate a certain amount of attenuation at low levels in order that the low-level mixing may be such that the sources can be mixed independently of one another.

In the mixing circuit which is described in Fig. 19 all the input channels are earthy on one side; although the authors state that they can get over this if necessary by providing a double control in these channels, we find it better to avoid circuits which are earthy on one side and which extend over any appreciable distance.

The output distributor is an ingenious device, but I cannot understand why the authors have set themselves such a difficult problem to solve. It seems unnecessary, having provided two completely separate groups of channels up to the main controls, and the facility of combining the main control outputs, to provide also the facility of combining the main amplifier outputs. Apparently the authors had in mind the possibility that two programmes, separately controlled and separately faded, might be required, with provision for taking each through its own main amplifier and combining the two in the transmitter. In the unlikely event of such arrangements being called for, it would be much more convenient and much easier to combine the programmes after the main output controls, and provision is made for this. A much simpler arrangement than the output distributor would have been to provide across the main output amplifier a simple trap valve and to connect loud-speakers across that, leading the main output straight through to the transmitter. With this arrangement the loud-speaker circuits would be completely isolated from the main programme chain. The authors state that in their main amplifier the output stage consists of two L.30 valves in push-pull, as a maximum output of + 22 db. (or 160 mW) is required; but it should be noted that the transmitter only requires + 15 db., there being a permanent loss of 7 db. in the output distributor.

Mr. J. Moir: Dealing with the reproduction of sound from film, I notice that the sound channel has been modified to give a frequency characteristic flat out to 8 kc./sec. with the rest of the chain flat out to higher frequencies. Some careful tests in America and England have indicated that it is inadvisable to operate with a flat characteristic, and the Society of Motion Picture Arts and Sciences recommends a loss of 10 db. at 8 kc./sec. In view of this, could the authors tell us what percentage of film is run with the range switch in the 8-kc./sec. position?

When the equipment was installed the standard method of propelling film through the sound gate was the use of toothed sprockets. This is known to introduce considerable sidebands, resulting in rather rough reproduction. Since that time various types of magnetic drive have appeared, rendering toothed sprockets unnecessary. Have the authors considered modifying the equipment to take advantage of this development?

With regard to the use of triodes in the first stage of the microphone amplifier, did the authors use triodes because they found that the specification regarding harmonic content could not be met with pentodes? The low input capacitance of a screened valve permits an increase in output from a low-level microphone, resulting in an improved signal/noise ratio in those cases where noise from the first valve is the limiting factor.

Finally, I should like to have some figures as to the overall signal/noise ratio for the whole equipment.

Mr. T. H. Bridgewater: On page 442 the authors discuss five methods which it was envisaged might possibly be needed for use in conjunction with the television studio. It may be of interest to point out that the fourth and fifth of these methods have been by far the most commonly used. The fifth method allows a greater number of sources to be controlled, so we have preferred to use the mixing panel as a straightforward 7-way balance-and-fade unit, and it has been quite successful. The fourth method, the diagram of which is shown in Fig. 2, works very satisfactorily. By using a ribbon microphone in the studio and so placing it that its direction of maximum response is perpendicular to the line of direction of the loud-speaker one can entirely eliminate any pick-up by the microphone, the whole of the gramophone music going straight through the amplifiers and faders and then into the transmitter, after being mixed with the studio sound.

Although the ribbon microphone would appear to offer valuable advantages, not only in the case I have mentioned but in others, particularly in a small studio, it has been found difficult to make as much use of it as we should have liked. The microphone is susceptible to air currents due to movement, and in a television studio it is almost impossible to set up a microphone in one position and leave it there for the duration of the performance, as in ordinary sound broadcasting. Most of the time a "boom" is being used and will be swinging around, sometimes very fast, while also being extended outwards and inwards. On account of these difficulties the moving-coil microphone is used much more than the ribbon type. Can the authors hold out any prospect of the development of a ribbon microphone, or a microphone with an equivalent directional property, which would stand the rough use it would have to suffer in a television studio?

Mr. P. G. A. H. Voigt: I can speak on this paper from two points of view: Firstly, some 10 to 15 years ago I was engaged on the design of apparatus for gramophone recording, and in many respects this apparatus is remarkably parallel to the apparatus used for television. Secondly, I am concerned with the quality of the sound coming from the Alexandra Palace television transmitter from the point of view of the user, as I am very often engaged in the demonstration of sound-reproducing apparatus the output of which is absolutely dependent upon the perfection of the input. Consequently I am very gratified to see the considerable trouble which has been taken to eliminate distortion as far as possible.

The only fault I can find with the paper is that all the frequency/response curves stop short at 10 000 cycles per sec. This is not the effective upper limit of audible frequencies, and I was therefore delighted to see that the authors showed a slide giving a characteristic curve going up to 16 000 cycles per sec.

One of the important links in an electro-acoustic chain of the kind described in the paper is the studio acoustics,

and some further information on this subject would be welcome. It may be that the reputed perfection of television sound is partly due to the fact that the incidental studio acoustics happen to be more favourable than usually obtain under broadcasting conditions.

As regards the microphones, when I was engaged in devising a suitable instrument I pinned my faith to a pressure microphone because I was of the opinion that any velocity microphone was liable to give misleading results. Nearly all television performances take place in an enclosed space, so that one has to deal with standing waves. Under such conditions, a 50-cycle note will be heard most loudly at the pressure antinode, which is about 5 ft. 6 in. away from the velocity antinode where a velocity microphone responds most. At the pressure antinode, it is quite conceivable that the ribbon microphone might not respond at all.

The ribbon is a mechanism which is capable of vibrating not only at its fundamental frequency but at all its harmonics, and the odd harmonics and the fundamental are capable of producing an electrical output from the microphone. Experimenting with a ribbon microphone on one occasion, I could trace a kind of reverberation at the fundamental and at its odd harmonics, as far as the eleventh. In my opinion it is important that a microphone should be aperiodic.

I believe that the pressure microphone described in the paper, although it has a deliberate mechanical resonance at 500 cycles per sec., behaves by virtue of the correcting circuit as though in effect it is aperiodic. Is this correct?

Is a breather provided for equalizing the pressures on the two sides of the diaphragm in the moving-coil microphone? I notice also that with the moving-coil microphone for face-on working the general trend is 1-db. slope per octave upwards, while in the case of the ribbon microphone the slope above 1 000 cycles per sec. seems to be in the other direction. Thus, whereas the moving-coil microphone gives a 3-db. rise between 1 000 and 5 000 cycles per sec., the ribbon microphone has a 4-db. drop over the same range. That means that if the gain is set for equal output of a 1 000-cycle fundamental from either type of microphone, there is a 7-db. difference in the output of a 5-kc./sec. harmonic. Does this difference in relative response account for the excessive sibilance which is noticeable on some announcements?

With regard to the switch provided for cutting bass in the ribbon-microphone amplifier, in the case where the microphone has to be used so near the sound source that the "law" of the microphone breaks down and it becomes "boomy," I would prefer to have a variable control.

I am pleased to see that the authors have had the courage to break away from the tradition of matching all outputs and inputs to a 600-ohm line. The nearly "open circuit" input arrangement has much to commend it, especially when the line is operated at about 1 volt peak signal. When I was using such a system, my input was normally a condenser potentiometer used as a volume control; thus I had the added protection that an unexpectedly high signal on the line would not overload the first valve in the main amplifier.

The "fold-back" principle is not unique to television. I once had the problem of grafting a vocal chorus in English on to a record which had been recorded in Rumania about a year before, and a similar arrangement was used. The record was put on the market to be sold in the ordinary way, and no one detected what had happened.

I am delighted to see that the peak modulation meter with instantaneous action and slow recovery is finding favour. I have described previously* the peak modulation meter which I used, and I note that my constant, namely a 5-sec. recovery period, is the one which the authors have also found the most convenient.

Regarding harmonic content, I am glad to see that the authors have had the courage to publish their figure for the harmonic content at low frequencies. I believe many specifications for radio sets only publish the harmonic content in some part of the scale where the adverse effect of too small a transformer is not disclosed.

Turning to the general subject of loud-speakers, I consider that a perfect loud-speaker, besides being free from amplitude distortion, should have a level response curve and a non-directional and aperiodic output. So far I do not believe anyone has produced such a perfect instrument. In the paper, the axial response of the loud-speaker used and its sound distribution are discussed, while in the description of the construction of the diaphragm it is pointed out that one part damps the preceding one. It is therefore obvious that the authors are well aware of the features which are desirable in a loud-speaker.

I take it that at Alexandra Palace headphones are used merely for checking circuits and not for balance and control purposes. When I was doing gramophone work I found that it was essential to balance by means of a loud-speaker. I preferred to use one which was rather better than the best gramophones on which the resulting record was to be played. It is my experience that if the musical balance has been suited to a poor reproducer, then a good reproducer is handicapped when trying to demonstrate its superiority, with detrimental results as regards both technical progress and sales.

I should like to know what the frequency characteristic of the microphone used for outside broadcasts is likely to be.

I come now to the difficulties I encounter when trying to demonstrate the quality of 7-metre reception. The first one is that, in plays, when the actors make unexpected noises, the quality frequently becomes exceedingly harsh. Is there any possibility of the microphone amplifiers being overloaded before the attenuators? The next and more important point is the variation in the tonal quality of the radiated programme. When using a set which had an independent treble and bass control I found that the occasions when both those controls could be left so as to give a level characteristic were surprisingly few. I regret to say that with almost every change in programme or change-over to gramophone or to film some juggling with the controls was necessary. I think that that kind of thing should be done at the source, particularly as gramophone records and films vary so much in their response.

Mr. P. W. Willans: I have found difficulty in understanding certain points regarding the rating of the level

* *Journal I.E.E.*, 1932, vol. 71 p. 632.

of the moving-coil microphone referred to in the paper. First of all, when the response of the microphone is stated to be − 66 db. it is not clear from the paper whether this refers to the voltage across the terminals of the coil, across the equalizer winding of the transformer, or across the high-resistance winding. Secondly, if a certain voltage level is to be used, independently of power load (as is the case in the rating of this microphone), there seems to be no point in taking as reference level a voltage which would, if developed across 200 ohms, give rise to a power dissipation of 1 milliwatt, when, at any rate in the case under consideration, there is no such resistance anywhere in the chain. It is to be noted that the rating both of the microphone and of the microphone amplifier involve open-circuit voltage levels, and had zero level been taken as 1 volt instead of 0·4472 volt the answer would have come out the same.

It seems a pity to depart from the conception of power rating in microphones just because they happen to have shunt equalizers. If we suppose the microphone to be replaced by a fictitious microphone which is a generator of internal resistance equal to the "static impedance" of the actual microphone and which produces an open-circuit e.m.f. identical with that produced by the actual microphone across its shunt equalizer, we may define the power rating of the actual microphone as being equal to that of the fictitious microphone. The gain of the microphone amplifier is then rated in the same manner as that of any other amplifier, and the sum of the two figures gives the same answer as is obtained from the voltage rating proposed in the paper. The advantage of the method here suggested is that, apart from uniformity, the figure of rating of the microphone does give an impression of its actual sensitivity, whereas, with the voltage rating proposed in the paper, the sensitivity may be anything until it is known what is the order of impedance (however variable) across which this voltage is developed.

I should be interested to know whether there has been any tendency for the turns of the moving-coil microphone to pick up interference inductively. With ribbon microphones it is comparatively simple to use an astatic arrangement of leads, but to do the same with the moving-coil microphone seems at first sight to be impossible.

I should also be interested to know how permanent-magnet microphones are adjusted for damping, in the absence of any control of magnetizing current.

Lastly, with reference to Fig. 7, it appears to me that the statement (page 445) "From this it will be noticed that the response of the microphone to frequencies below 1 000 cycles per sec. is substantially circular" is somewhat misleading. It is true in so far as the curve corresponding to the next lower frequency exhibited, namely 200 cycles per sec., is substantially circular, but that leaves rather a large gap in the frequency scale about which we are told nothing. If the implication is that the 1 000-cycle curve is itself circular, I cannot agree that it is so either in fact or in effect. The whole family of curves leads one to the conclusion that some of the sensitivity of this remarkable instrument might profitably be sacrificed to achieve a reduction in size and consequent improvement in respect of directional irregularities.

Mr. F. L. Coombs: The authors suggest that we should accept a matching impedance of 200 ohms in preference to the usually accepted impedance of 600 ohms in cases where the length of connecting wire is relatively short. I had always understood, however, that the matching of a cable was determined not by any accepted figure but by the characteristic impedance of that particular cable. The principle of accepting any kind of matching impedance as standard is fundamentally unscientific. As a matter of fact, why one gets better results with the 200-ohm impedance is not because it is a better figure but because 200 ohms is much nearer the characteristic impedance of the average cable than 600 ohms. A parallel case is the characteristic impedance of the Post Office overhead system. The theoretical value is not 600 ohms; that is a practical value, but we assume it will be approximately correct. When dealing with outside broadcasts we must take into consideration whether the line employed is an open overhead feeder (approximately 600 ohms) or an underground feeder (nearer 200 ohms).

Dr. L. E. C. Hughes: Ten years ago, when I was working in a large firm on microphone circuits, the impedance level employed was adopted from stabilized American practice and invariably was 200 ohms; the other firm using such circuits, and also the B.B.C., favoured a figure of 400 ohms, which we thought too high, but not seriously so. The actual level is of no real consequence, provided that the series loss of leads is not appreciable with the lower impedance-levels, and that the shunt capacitance of the leads does not upset the response of output transformers at the upper impedance levels. The leads are not sufficiently long for wave attenuation, the capacitance being merely a small bridging loss. This is naturally mitigated by loading the receiving transformer.

The response of a microphone is most easily and irrefutably stated as $E^2/(4R)$, where E is the effective internally generated electromotive force when a stated sound-level [e.g. that equivalent to an alternating acoustic pressure of 1 (r.m.s.) dyne per cm^2 in a free wave at the location of the microphone in its absence] is applied to the microphone, and R is the source-impedance of the microphone or the load into which it works. This definition of response is consistent with Thévénin's theorem as applied to any microphone, and theoretically implies that the maximum power is being extracted from the microphone for a given sound-level applied to it. The above alternating pressure is not usually the pressure operating the microphone, but any ratio between these pressures is part of the response of the microphone, arising from geometrical reflection, and should be included in the response, which is naturally plotted in decibels against a logarithmic frequency-base.

I agree with Mr. West that we need a specification for the response and radiation from loud-speakers, such as is given, and easily attained, for high-quality sound-film reproduction by the Society of Motion Picture Arts and Sciences.* Broadcast radio engineers suffer considerably in designing receiving sets through the lack of a reasonable specification.

The so-called fold-back circuit is by no means novel—it was used in a sound-film studio in which I was working in 1931, and was then considered the ordinary way to

* "Motion Picture Sound Engineering" (Chapman and Hall), p. 98.

add noises and singing in the electrical circuit, in synchronism with extras performing in dumb-show so as not to distract the principal artists while they were being photographed. The fold-back circuit is analogous to prescoring, which is in regular use in sound-film production for musical sequences. The simplest method of mixing is to apply each microphone output, amplified if necessary, to the grid of a valve through a potentiometer and to parallel as many such anodes as desired. There is no way of avoiding the inevitable loss in mixing, but any microphone circuit would have ample gain to compensate for this loss. There is no meaning in stating the output level of a microphone, without stating also the sound (or phon) level of the sounds applied to it.

Messrs. I. L. Turnbull and **H. A. M. Clark** (*in reply*): We are interested to observe that Mr. Kirke considers that the system described in the paper contains a number of desirable features. We agree that for a system as large as that operating at Broadcasting House the use of amplification in each channel before mixing would increase the initial cost of the equipment.

In reply to Mr. West, we agree that the provision of a loud-speaker having a performance similar to that of the remainder of the equipment, and operating under known acoustic conditions, would be very desirable were conditions of space and cost unfettered. It has been found, however, that, for balancing purposes, the use of a loud-speaker which more than covers the fundamental range of orchestral frequencies and, in addition, complies with the practical limitations of size and portability, is quite satisfactory. It would certainly be of value if a standard method of assessing the quality of a loud-speaker involving the polar response could be generally accepted.

With regard to Mr. Colborn's remarks, although there are practicable circuits with which equalized microphones of this type may be mixed without interaction, it was felt that such a low mixing level was undesirable in a situation where crosstalk from vision and power circuits was likely. As he says, the use of balanced inputs to the mixing circuits would be advisable where the input lines are of considerable length. With regard to the combination of the main amplifier outputs in the output distributor, the original objects were: (*a*) the permanent independent connection of both amplifiers to the transmitter when one of them is acting as a standby in a single-channel transmission, and (*b*) the provision of a separate loud-speaker monitor for each of the main amplifier channels, if required.

With reference to Mr. Moir's remarks, we regret that we have no information as to the percentage of film which the B.B.C. transmit with the full frequency range. The defects due to the use of a sprocket drive were recognized at the time of installation, but the projectors in question were of a type very suitable for television transmission. Sound gates of the sprocketless type are, however, now in use.

It is recognized that the use of pentodes in the first amplifier stages is sometimes advantageous, and such a valve is used for the first stage of the talkback amplifier. For transmission microphone amplifiers, however, no pentode was available with an anode circuit noise and hum level as low as in the triode referred to in the paper.

With regard to Mr. Bridgewater's query as to the use of a ribbon microphone on a boom, it is feared that such microphones will always be more prone to air-movement noise than types in which a less-compliant moving system is employed.

Mr. Voigt regrets that the frequency/response curves given stop short at 10 000 cycles per sec. Although the frequency response of the electrical system could have been shown to 16 000 cycles per sec. or higher, 10 000 cycles per sec. is, at the moment, the limit to which accurate acoustic frequency/response characteristics are supplied by the National Physical Laboratory. With regard to the studio acoustics, we would refer Mr. Voigt to the paper by Messrs. Macnamara and Birkinshaw published in the *Journal* last December.* We regret that we do not appreciate why the pressure microphone should be less subject to the effects of standing waves in the studio than a velocity microphone, as Mr. Voigt appears to suggest. Mr. Voigt is correct in assuming that the pressure microphone acts aperiodically when used in conjunction with its equalizing circuit. Breathing arrangements are provided which enable the pressure on both sides of the moving-coil diaphragm to be equalized. In television studios, where the microphone position is generally some distance above the speaker's head, we feel that a fairer comparison between relative response of the two types of microphone used is obtained by comparing the ribbon microphone frequency characteristic with the random, rather than the axial, characteristic of the moving-coil microphone. We regret that we are unable to give Mr. Voigt any information as to the frequency characteristic of the microphone used by the B.B.C. for outside transmissions. There should be no danger of microphone amplifier overload, provided that the pre-set gain-controls on the microphone amplifiers are suitably adjusted. Further, apart from the upper limitation which is necessary on the frequency characteristic of recorded sound transmissions, there is nothing in the performance of the equipment, apart from the studio characteristics, which should give rise to the variation in quality noted.

With regard to Mr. Willans's first comment, the response given in Section (2.116) of the paper is stated to be that of the microphone alone, the actual microphone terminals being implied. His suggestion for the rating of an equalized microphone is essentially sound and is the most suitable method for fundamental considerations of sensitivity and noise level. However, since the microphone equalizer is intimately associated with the amplifier by means of a three-winding input transformer, the separate testing of the equalized microphone and the unequalized amplifier is impracticable. Moreover, since the zero power-level of 1 milliwatt and an almost universal circuit impedance of 200 ohms are in use, the voltage calibration of the testing equipment supplied must be on a basis of a zero level corresponding to 0·4472 volt. For this reason, the open-circuit voltage rating discussed in the paper has been based on this zero level. In large stray alternating-current fields there is a possibility of magnetic induction direct into the coil of the moving-coil microphone. In the case of the permanent-magnet type a field-magnet

* *Journal I.E.E.*, 1938, vol. 83, p. 729.

is used, consisting of a stable material such as "Alnico," and the gap flux is adjusted after initial magnetization by the process of demagnetizing in small steps. We regret the loose statement with regard to the polar characteristic to which Mr. Willans draws attention. If the statement "substantially circular" is taken to imply a uniform polar response within 3 db., a more correct limiting frequency would be 700 cycles per sec.

We should like to point out to Mr. Coombs that the 200 ohms circuit impedance was not chosen arbitrarily but for the reason that it more nearly represents the average characteristic impedance of the cables employed than does 600 ohms.

With regard to Dr. Hughes's remarks on microphone response, in the case in question, since the microphone and load impedances are dissimilar and extremely variable with frequency, the simple definition which he gives is inadequate. In this connection we would refer him to the remarks above in our reply to Mr. Willans.

PROCEEDINGS OF THE INSTITUTION

940TH ORDINARY MEETING, 5TH JANUARY, 1939

Dr. A. P. M. Fleming, C.B.E., M.Sc., President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting held on the 15th December, 1938, were taken as read and were confirmed and signed. A list of candidates for election and transfer, approved by the Council for ballot, was taken as read and was ordered to be suspended in the Hall.

The President announced that during the month of December 59 donations and subscriptions to the Benevolent Fund had been received, amounting to £67. A vote of thanks was accorded to the donors.

The following list of donors to the Library was taken as read, and the thanks of the meeting were accorded to them: Admiralty; Agent-General for Tasmania; Air Ministry; American Institute of Electrical Engineers; American Radio Relay League, Inc.; American Society of Mechanical Engineers; American Telephone and Telegraph Company; Commander Rollo Appleyard, O.B.E.; Association of American Railroads; Association of Engineers in Burma; Association of Municipal Electrical Undertakings in South Africa; Association Suisse des Électriciens; Associazione Elettrotecnica Italiana; The Astronomer Royal; Messrs. Babcock and Wilcox, Ltd.; R. Baldwin; Messrs. Benn Bros., Ltd.; Messrs. Bennis Combustion, Ltd.; L. D. Bliss; D. J. Bolton, M.Sc.(Eng.); Major C. H. Brazel, M.C.; British Acetylene Association; British Association for the Advancement of Science; British Broadcasting Corporation; British East African Meteorological Service; British Electrical and Allied Industries Research Association; British Electrical Development Association; British Engine Boiler and Electrical Insurance Co., Ltd.; British Engineers' Association (Inc.); "British Engineers Export Journal"; "British Plastics and Moulded Products Trader"; British Standards Institution; Bureau of Standards, U.S.A.; Canadian Bureau of Statistics; Canadian Engineering Standards Association; Canadian Manufacturers' Association; Central Electricity Board; Centro Volpi di Elettrologia; Messrs. Chapman and Hall, Ltd.; Messrs. Cheap Steam, Ltd.; Conférence Internationale des Grands Réseaux Électriques à Haute Tension; Commonwealth of Australia; Copper Development Association; D. Csillery; Lady Dawson; Department of Scientific and Industrial Research; Departement van Verkeer en Waterstaat; Derby Society of Engineers; T. J. Digby; A. B. Eason, M.A.; Electrical Contractors Association; Electrical Engineers' Club, King's College, Newcastle-on-Tyne; "Electrical Review"; Electricity Advisory Committee, N.S.W.; Electricity Commissioners; Electricity Supply Authority Engineers' Association of New Zealand; Electricity Supply Commission, South Africa; Electrodepositors' Technical Society; Elektrotechnický Svaz Ceskoslovensky; The English Universities Press, Ltd.; J. F. Field, B.Sc.; E. M. Flamme; Sir Ambrose Fleming, M.A., D.Sc., F.R.S.; Messrs. Fuller Electrical and Manufacturing Co., Ltd.; Messrs. General Electrical Company, N.Y.; General Post Office (Public Relations Department); Messrs. Sir Alexander Gibb and Partners; A. E. Greenlees; Messrs. Hadfields, Ltd.; B. Hague, D.Sc.(Lond.); E. Harper; Messrs. W. T. Henley's Telegraph Works Co., Ltd.; T. E. Herbert; F. W. Hewitt, M.Sc.; Messrs. High Duty Alloys, Ltd.; Home Office; Messrs. F. A. Hughes and Co., Ltd.; Hull Association of Engineers; W. S. Hunt; Hydro-Electric Power Commission of Ontario; W. S. Ibbetson, B.Sc.; Illuminating Engineering Society (U.S.A.); Incorporated Municipal Electrical Association; Incorporated Radio Society of Great Britain; Indian Institute of Science; Indian Posts and Telegraph Department; Institute of Engineers (India); Institute of Physics; Institute of Radio Engineers, Inc.; Institution of Civil Engineers; Institution of Engineers-in-Charge; Institution of Professional Civil Servants; Institution of Radio Engineers (Australia); Institution of the Rubber Industry; International Association for Testing Materials; International Electrotechnical Commission; International Engineering Congress, Glasgow; Iron and Steel Institute; Japan Electric Association; Japanese Electrotechnical Committee; Messrs. Johnson and Phillips, Ltd.; K.F. Koehler Verlag; R. Keen, B.Eng.; J. M. Kennedy, O.B.E.; Messrs. W. King, Ltd.; E. W. Lancaster; F. W. Lanchester, LL.D., F.R.S.; Leeds Association of Engineers; Liverpool Engineering Society; London and Home Counties Joint Electricity Authority; Messrs. Longmans, Green and Co.; Messrs. McGraw-Hill Publishing Co., Ltd.; Messrs. Macmillan and Co., Ltd.; Manchester Association of Engineers; Meteorological Office; Messrs. Methuen and Co., Ltd.; Mines Department; Ministère des Travaux Publics; Ministry of Transport; Messrs. Mond Nickel Co., Ltd.; Mrs. W. M. Mordey; John

Murray; Col. The Hon. A. Murray, C.M.G., D.S.O.; National Confederation of Employers' Organisations; National Electrical Manufacturers Association; National Physical Laboratory; Messrs. George Newnes, Ltd.; New Zealand Hydro-Electric Development; New Zealand Post and Telegraph Department; Nigerian Public Works Department; H. Norinder, Ph.D.; North-East Coast Institution of Engineers and Shipbuilders; Norwegian Watercourse and Electricity Department; Oxford University Press; C. Parsons, B.Sc.; Prof. E. S. Pearson, D.Sc.; L. Peter; Physical Society; Messrs. Sir Isaac Pitman and Sons, Ltd.; Messrs. Pritchett and Gold and E.P.S. Co., Ltd.; W. S. Procter; Public Works, Roads and Transport Congress and Exhibition Council; Messrs. Quasi-Arc Co., Ltd.; E. T. A. Rapson, M.Sc.(Eng.); R.C.A. Institutes Technical Press; Reale Accademia D'Italia; J. H. Reyner, B.Sc.; R. C. H. Richardson; S. R. Roget; A. Roth, Dr.-Ing.; Royal Alfred Observatory, Mauritius; A. Rubin; H. M. Sayers; Messrs. Science et Industrie; Science Museum; M. G. Scroggie, B.Sc.; C. F. Smith, D.Sc.; Prof. S. P. Smith, D.Sc.; Société Financière de Transports et d'Entreprises Industrielles; Messrs. E. and F. N. Spon, Ltd.; Standards Association of America; Messrs. Standard Telephones and Cables, Ltd.; Surveyor-General of India; Svenska Teknologföreningens; Swedish Consul-General; The Technical Press, Ltd.; United States Department of Commerce; The University Tutorial Press, Ltd.; B. Van der Pol, D.Sc.; Verband Deutscher Elektrotechniker; R. C. Walker; S. J. Watson; Messrs. Where to Buy, Ltd.; Wirtschaftsgruppe Elektroindustrie; A. P. Young, O.B.E.; and H. T. Young.

A paper by Mr. J. I. Bernard, B.Sc.Tech., Associate Member, entitled "The Application of Electric Heating to Domestic Hot-Water Supply Systems" (see page 1), was read and discussed. A vote of thanks to the author, moved by the President, was carried with acclamation.

INSTITUTION NOTES

CONVERSAZIONE OF OVERSEAS MEMBERS

A Conversazione of members from overseas and their ladies was held in the Institution building on Tuesday evening, 13th June, 1939, the attendance being 135. After the guests had been received by the President (Dr. A. P. M. Fleming, C.B.E.), suported by the Council, a short address was delivered in the Lecture Theatre by Mr. Ll. B. Atkinson, Past President, on "Institution Recollections." At the conclusion of the address a talking film of Colonel R. E. Crompton., C.B., F.R.S., was exhibited. A reunion then took place in the Library.

The following members temporarily in England from overseas were present: J. D. Addison (India), I. M. E. Aitken, B.Sc. (India), F. K. Akhurst (New Zealand), H. S. Bulley (India), V. A. M. Bulow (Iraq), L. F. Burgess, M.C. (Australia), H. A. Campbell (Jamaica), R. D. Crofton, B.Sc.(Eng.) (China), H. E. Crowcroft (China), F. D'Souza (India), W. A. Duff, M.A. (South Africa), H. C. Harris (India), P. S. E. Jackson (India), J. Kemp, B.Sc. (Iraq), M. A. A. Khan, B.Sc.Tech. (India), P. D. McNeil (New Zealand), G. E. Martin, M.A. (India), R. G. Mukherji, M.Sc. (India), W. B. R. Mumford (India), C. Murray, B.Sc.(Eng.) (India), G. A. Murray (Australia), D. M. Myers, B.Sc., B.E., D.Sc.(Eng.) (Australia), A. S. Phillips (China), S. E. Povey (India), J. O. Renaut (New Zealand), H. G. Sale (India), G. R. Simpson (New Zealand), I. D. Stevenson (New Zealand), K. J. Thouless, M.A. (India), D. M. Tombs, B.Sc.(Eng.) (New Zealand), F. H. Turrell, B.Sc.(Eng.) (Malaya), J. D. A. Vincent (India), C. R. Webb (China), and H. S. Wilson (British Guiana).

SCHOLARSHIPS

The following Scholarships have been awarded for 1939 by the Council:—

Ferranti Scholarship (Annual Value £250; tenable for 2 years)

A. E. Chester, M.Sc. (Manchester University).

Duddell Scholarship (Annual Value £150; tenable for 3 years)

D. E. Thomas (St. Clement Danes Grammar School, London).

Silvanus Thompson Scholarship (Annual Value £100, plus tuition fees; tenable for 2 years)

L. E. Ebourne (Cadbury Bros., Ltd., Birmingham).

Swan Memorial Scholarship (Value £120; tenable for 1 year)

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The Council have made the following grants for 1939–1940 for research purposes:—

£50 to R. K. Beattie, M.Sc. (Manchester University).

£25 to P. H. Longman (Queen Mary College, London).

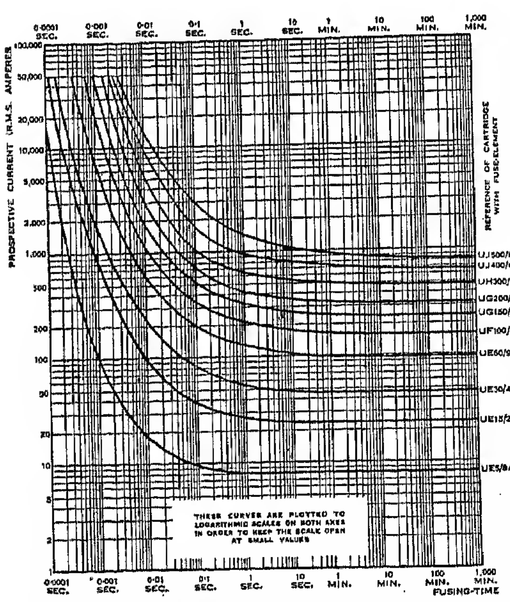
£25 to G. F. Shute, B.Sc. (University College, Nottingham).

FUSES: THEIR FUSING-FACTOR

USE
REYROLLE
CARTRIDGE
FUSES
REFUSING
ALL
OTHERS
IN
FACT OR
FANCY

A famous man, writing about the appropriate proportioning of faculties, said, "The body consists not of one member but of many. If the ear were to say, 'Because I am not the eye, I do not belong to the body', that does not make it no part of the body. If the body were all eye, where would hearing be? If the members all made up one member, what would become of the body? As it is, there are many members and one body. The eye cannot say to the hand, 'I have no need of you'. Quite the contrary."

TO COME TO FUSES:



Current/fusing-time curves of Reyrolle cartridge-fuses

B.S.88-1939 specifies fusing-factors appropriate to the other cardinal items of performance, so that fuses complying with it are neither too hot nor too cold, and neither so far from fusing that they never fuse nor so close to it that they never do anything else; in a word they are well-proportioned entities

• • •

A rather artificial dividing-line—a distinction without a real difference—is drawn between over-currents and short-circuit currents; Reyrolle cartridge-fuses are available for either purpose

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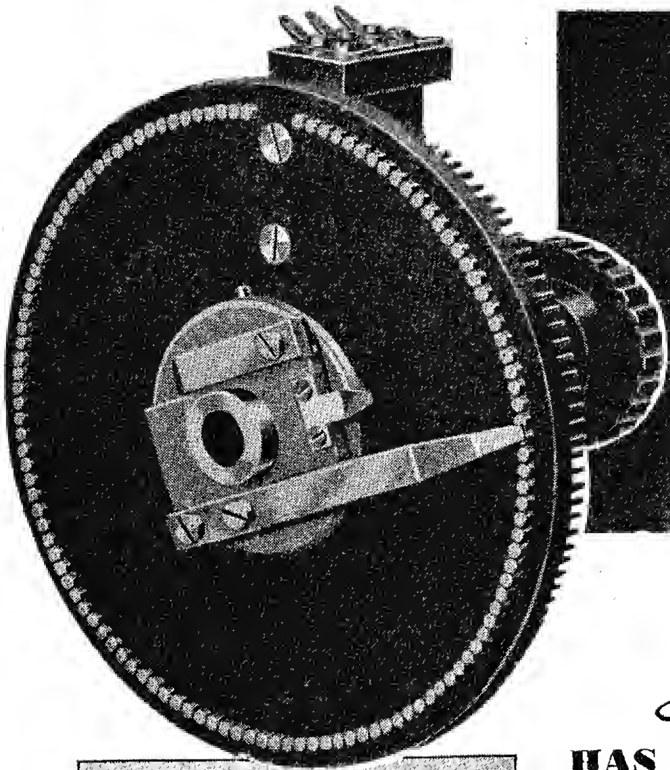
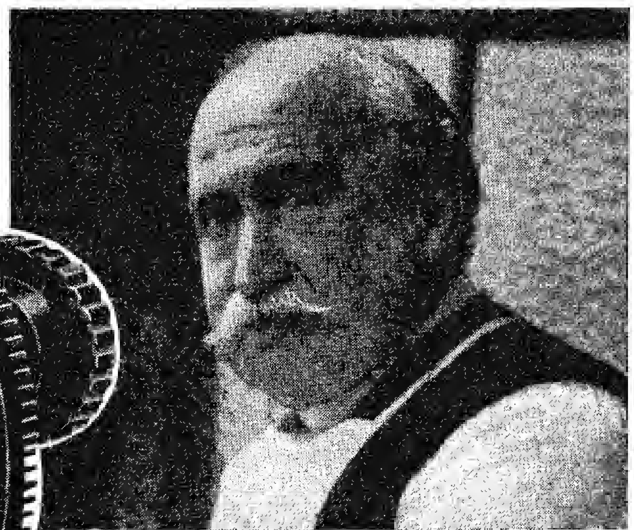
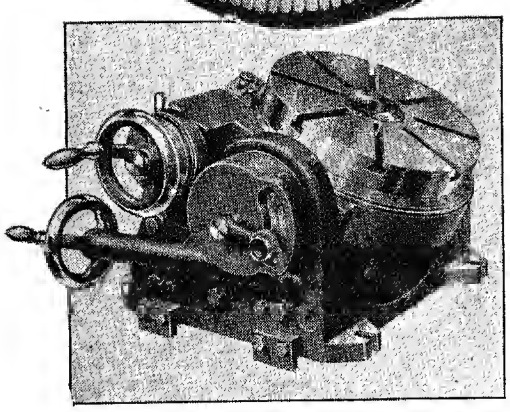
HEAD OFFICE AND WORKS
HEBBURN-ON-TYNE ENGLAND

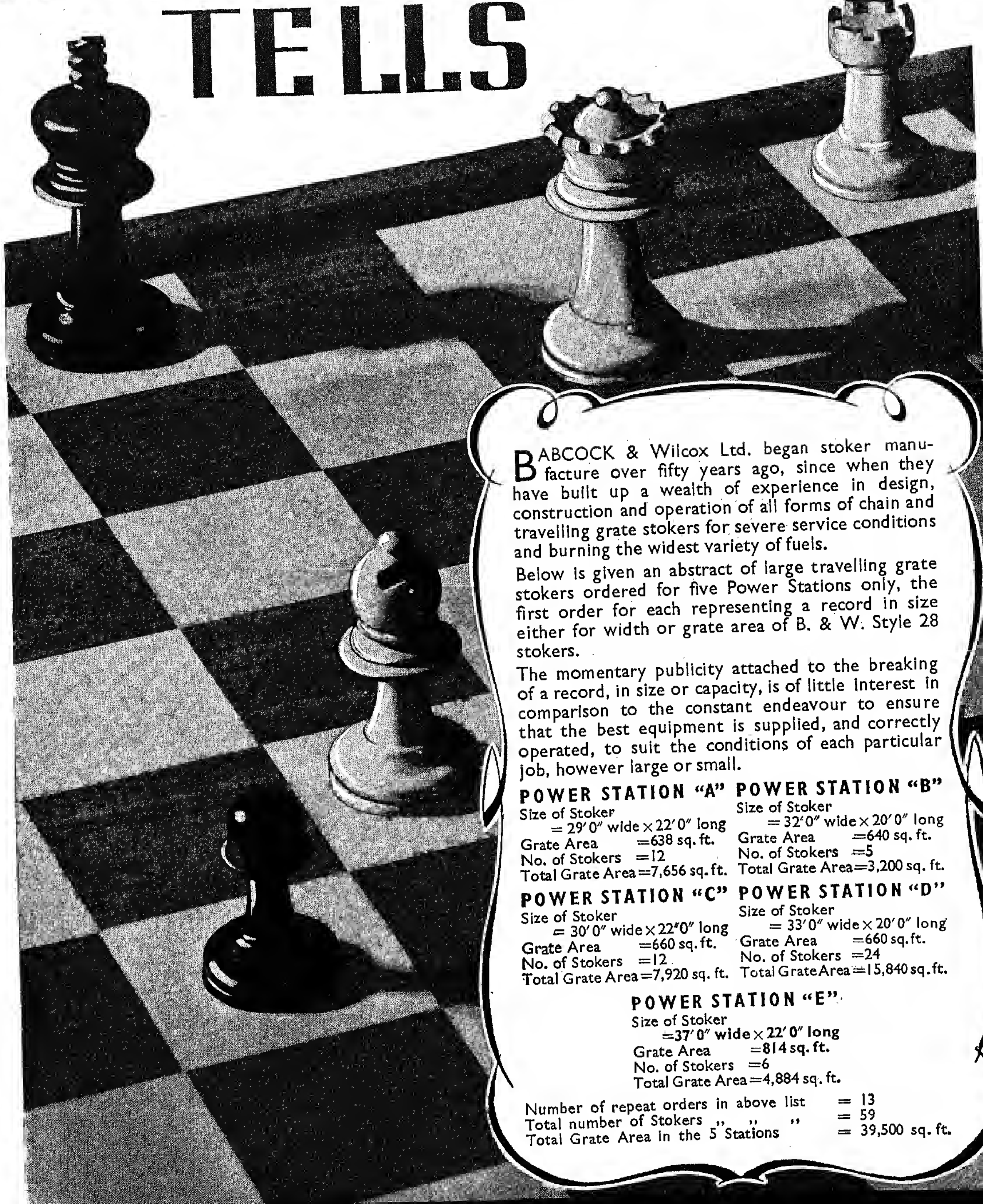






A Circular Table used at Muirhead's in the production of the 121 Stud Switch illustrated at top of page.

EXPERIENCE TELLS



BABCOCK & Wilcox Ltd. began stoker manufacture over fifty years ago, since when they have built up a wealth of experience in design, construction and operation of all forms of chain and travelling grate stokers for severe service conditions and burning the widest variety of fuels.

Below is given an abstract of large travelling grate stokers ordered for five Power Stations only, the first order for each representing a record in size either for width or grate area of B. & W. Style 28 stokers.

The momentary publicity attached to the breaking of a record, in size or capacity, is of little interest in comparison to the constant endeavour to ensure that the best equipment is supplied, and correctly operated, to suit the conditions of each particular job, however large or small.

POWER STATION "A"
Size of Stoker = 29′ 0″ wide × 22′ 0″ long
Grate Area = 638 sq. ft.
No. of Stokers = 12
Total Grate Area = 7,656 sq. ft.

POWER STATION "B"
Size of Stoker = 32′ 0″ wide × 20′ 0″ long
Grate Area = 640 sq. ft.
No. of Stokers = 5
Total Grate Area = 3,200 sq. ft.

POWER STATION "C"
Size of Stoker = 30′ 0″ wide × 22′ 0″ long
Grate Area = 660 sq. ft.
No. of Stokers = 12
Total Grate Area = 7,920 sq. ft.

POWER STATION "D"
Size of Stoker = 33′ 0″ wide × 20′ 0″ long
Grate Area = 660 sq. ft.
No. of Stokers = 24
Total Grate Area = 15,840 sq. ft.

POWER STATION "E"
Size of Stoker = 37′ 0″ wide × 22′ 0″ long
Grate Area = 814 sq. ft.
No. of Stokers = 6
Total Grate Area = 4,884 sq. ft.

Number of repeat orders in above list	= 13
Total number of Stokers " " "	= 59
Total Grate Area in the 5 Stations	= 39,500 sq. ft.

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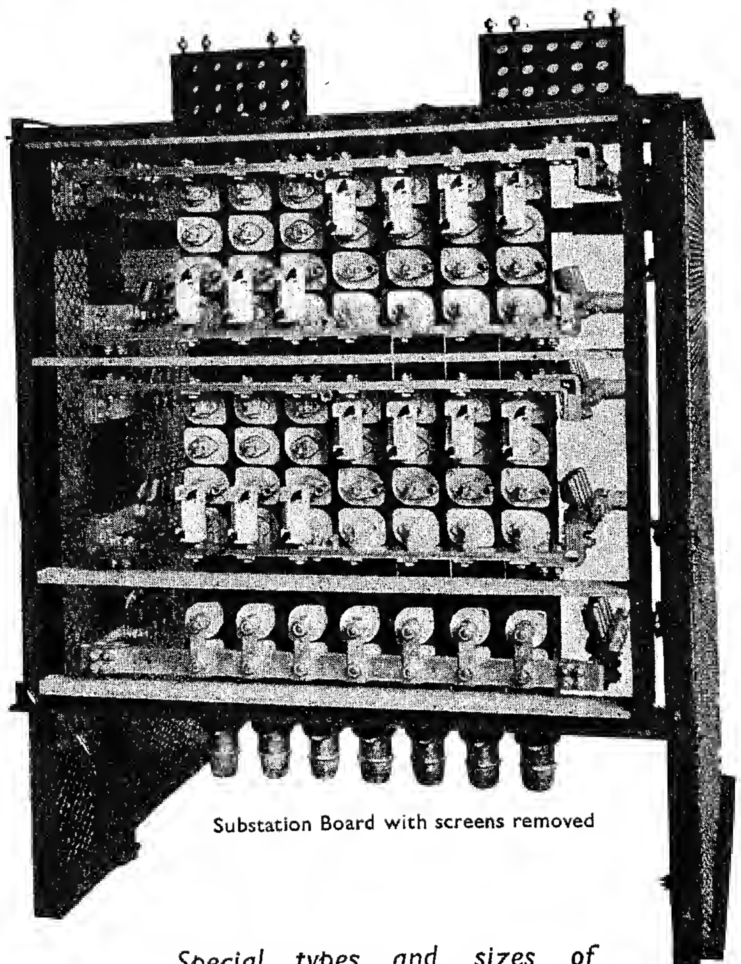

Substation Board with screens removed

Two-phase, 3-Wire, Selective Type Board with "J"-type Fuses.

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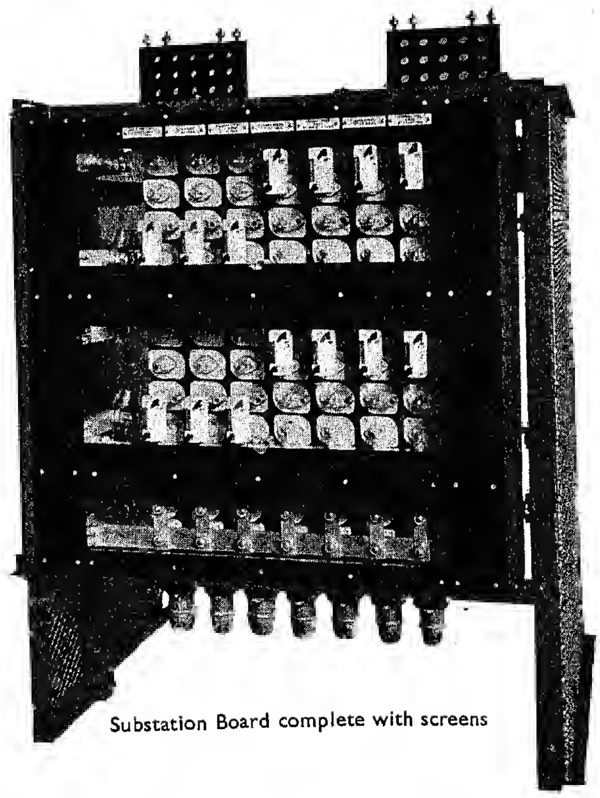

Substation Board complete with screens

Special types and sizes of Substation Boards can be made up to suit customers' own specifications or requirements.

We shall be pleased to submit suggestions, drawings, etc., upon receipt of particulars.

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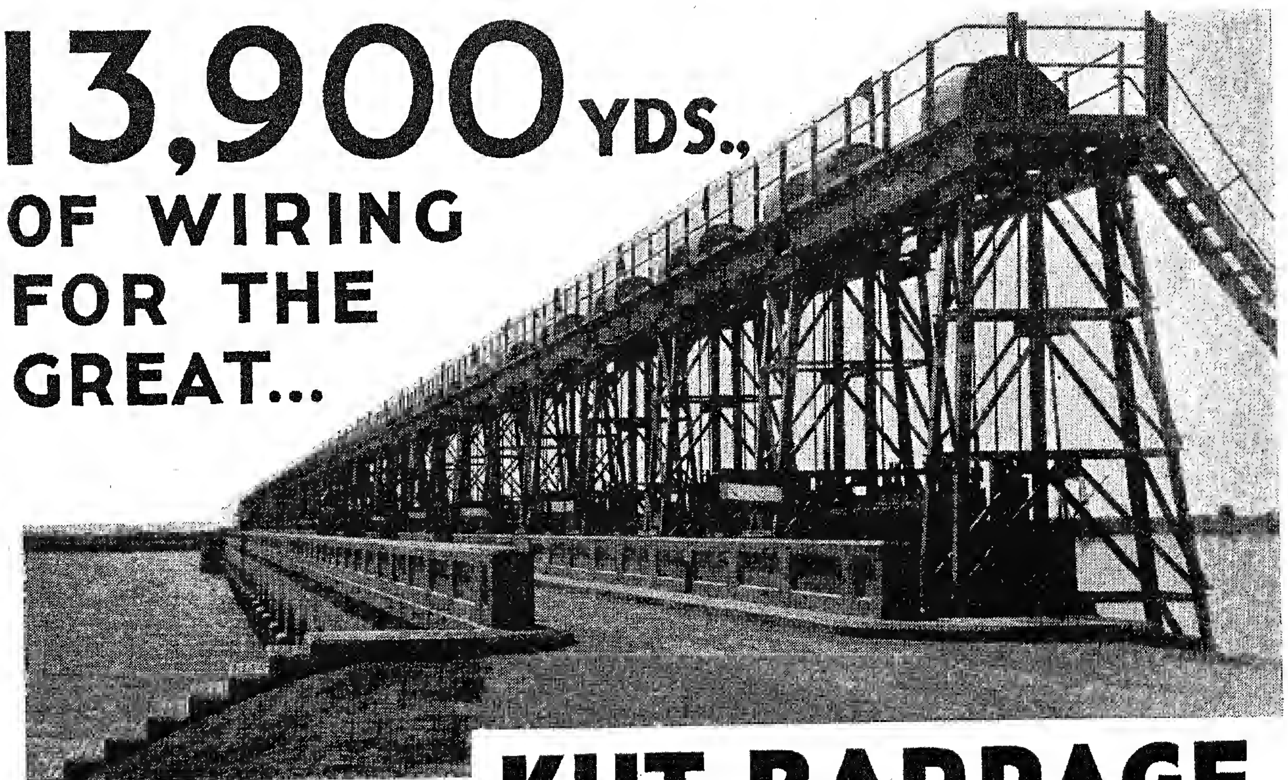
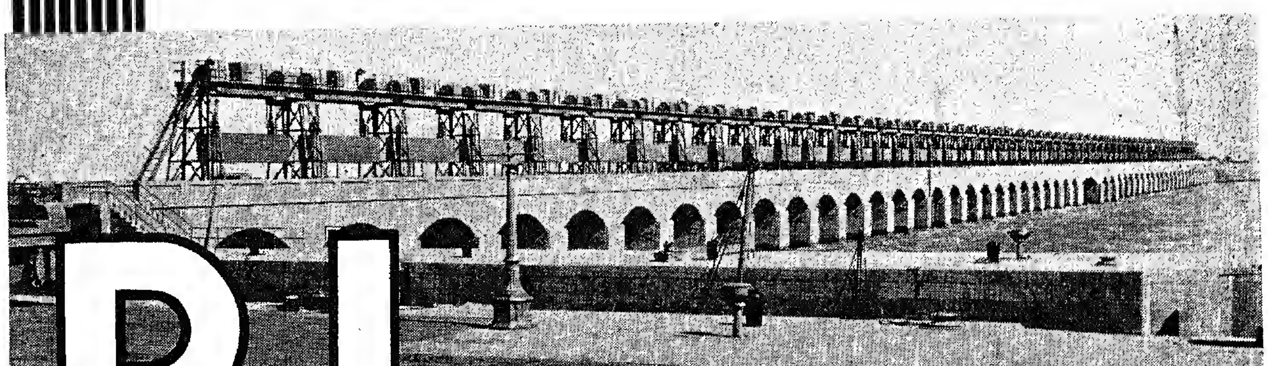


KUT BARRAGE

One of the most striking features of the great scheme for using the waters of the River Tigris to irrigate the surrounding area is the huge barrage dam built across the river at Kut el Amara. The whole of the wiring used in connection with this barrage by the contractors, Messrs. Balfour Beatty & Co. Limited of London, consists of **B.I.** Paper Insulated and Rubber Insulated Cables. Approximately 13,900 yards of cable were used, including special dredge cables for the operation of floating pumps. The Consulting Engineers to the Irak Government were Messrs. Coode, Wilson, Mitchell & Vaughan Lee.



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